DOD Future Energy Resources

Proceedings of Workshops Held at
The National Defense University

Sponsored by:

Office of Naval Research
Naval Research Laboratory
National Energy Technology Laboratory
National Defense University

Workshop Topics and Dates

Non-Renewable Energies	**December 17, 2002**
Biomass, Ocean, Hydrates and Hydrogen	**May 7-9, 2003**

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2003**	2. REPORT TYPE	3. DATES COVERED **00-00-2003 to 00-00-2003**

4. TITLE AND SUBTITLE **DOD Future Energy Resources. Proceedings of Workshops Held at the National Defense University**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **National Defense University,300 5th Avenue SW, Fort Lesley J. McNair,Washington,DC,20319**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Non-Renewable Energies, December 17, 2002 Biomass, Ocean, Hydrates and Hydrogen, May 7-9, 2003

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**90**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

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EXECUTIVE SUMMARY

As we enter the 21st century, the Department of Defense (DOD) remains critically dependent on oil from petroleum for operational energy and for all force projection. Although this has worked well historically, with DOD simply being one of the major consumers of commercial energy sources, there are concerns that this picture may not continue throughout the 21st century. In response to concerns about U.S. and global depletion of cheap petroleum resources and the particular impact of this on future DOD energy resource needs, a series of workshops were held during 2002 and 2003 at National Defense University. These workshops were specifically aimed at the policy, geopolitics, economics, and technological aspects of future energy supply and demands, attempting to answer questions about the possible need for DOD engagement with industry and with the Department of Energy (DOE) on future energy resource issues. Particular issues addressed in the workshops and in this report include: the role of DOD in current and near future development by the oil and gas industry; the role of DOD in national and international future energy programs; how estimates of future availability and cost of hydrocarbon fuels will impact DOD; the need for a DOD long term strategy and policy regarding potential energy shortages; and the effects of environmental constraints on DOD energy options.

The first workshop concluded that the major DOD requirement for energy in the next 50 years would remain liquid hydrocarbons, but that there was grave disagreement as to whether this requirement could continue to be met as it has in the past. This led to the further conclusion that DOD would be very wise to begin to more closely monitor this situation and take appropriate actions as necessary.

The remaining three workshops in the series focused on potential future energy replacements for oil with an emphasis on DOD needs. The areas chosen for detailed consideration were biomass, ocean energy, gas hydrates, and hydrogen. No single alternate energy resource offered a clear choice for DOD future energy resource needs.

The workshop series was not designed to provide definitive answers to the questions posed above, but rather to provide reasonable definition of the issues and areas that require more detailed study. Although an immediate energy crisis situation was not identified for DOD it was clear that a crisis of either supply or cost was building; but no consensus could be reached about specific time lines. However, it now appears that the time required to provide alternative solutions to cope with the impending crisis now exceeds the uncertainty regarding when a crisis for DOD will occur.

Thus, the two major recommendations from the workshop series were that DOD immediately conduct an in-depth study to identify the S&T (and later the R&D) needed to assure that its future fuel and energy needs are met. In this regard, consideration should be given to establish a position in the office of the Undersecretary of Defense for Policy that would be responsible for *future* DOD energy needs. This position would report directly to the Secretary of Defense and would coordinate with the energy and fuel offices in the individual services and with the office of the Secretary of Energy. The results of the in-depth DOD study would be reported to the Secretary of Defense, the Undersecretary of Defense for Policy, and the Secretary of Energy with the necessary information upon which to establish future programs.

Chapter 1

SETTING THE STAGE: DOD ENERGY CRISIS–FACT OR FICTION?

Dennis Hardy, Bhakta Rath, Burton Hurdle, Homer Carhart, and Fred Saalfeld

> *This is the report of a series of workshops covering the issues of future energy requirements of the Department of Defense (DOD) and the associated national security concerns as they relate to the national policies and global geopolitical environment. The objective is to conduct an analysis of these issues as deliberated by international experts on energy, economics, law, and geo-politics and to provide guidance to DOD in developing appropriate near and long-term strategies and execution plans.*
>
> *Vice Admiral Paul. G. Gaffney, II*
> *President, National Defense University*
> *June 2003*

Overview

Global consumption of energy is staggering. Furthermore, the U.S. Department of Energy (DOE) projects the total world consumption to rise by 59% between 1999 and 2020, from 382 to 607 quads per year (one quad being defined as 10^{15} BTU and equivalent to more than 7 billion gallons of petroleum).[1] The same report predicts a 20% increase of carbon dioxide emissions equivalent to approximately ten billion metric pounds of carbon. Another complication in the energy equation is that global population will increase from 6.0 to 7.5 billion.

The impact of these projections on DOD may have long-range and profound implications. As an example, in 2001, DOD paid more than $5.2 billion for energy and consumed 5.6 billion gallons of fuel.[2] Historically, fossil fuels derived from hydrocarbon-based products have been the primary raw materials and the basis for U.S. military might and long-range power projection. In the United States, petroleum-based fuel use is twice that of coal or natural gas consumption and four times that of nuclear energy or

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[1] International Energy Outlook 2002, DOE/EIA 0484, Washington, DC.
[2] Defense Energy Support Center Annual Fact Book 2001, 24th Edition.

renewable energy resources.[3] Virtually the entire existing energy related infrastructure, both for DOD and the United States as a whole, relies on fossil fuels. Undoubtedly, DOD will remain dependent on hydrocarbon combustion for the foreseeable future. However, neither DOD nor the country can afford to ignore the long-term impacts of continued hydrocarbon combustion. At some point the present feedstock will become depleted and/or environmental regulations will limit the use of fossil fuels. It is essential, therefore, that DOD develop a long-term plan to use alternative energy sources.

Background

Driven by these concerns, members of the defense scientific community designed a series of workshops to review the current status, future availability, and use of energy as it specifically pertains to DOD. These workshops were held at the National Defense University (NDU) between December 2002 and May 2003. Organizers and sponsors of these workshops were the Office of Naval Research (ONR), Naval Research Laboratory (NRL), National Energy Technology Lab (NETL), and National Defense University (NDU).

The primary objective of these future DOD energy issues workshops was to develop a better understanding of the current energy resources and fuel consumption of DOD in reference to the role of economics as well as global and national geopolitics. The first workshop introduced the series and laid out the potential problems from the DOD perspective by dealing with near-term issues, including discussions of non-renewable current and future fuels as well as nuclear energy. Follow-on workshops focused on other alternate energy sources such as biomass, ocean thermal, waves and tides, and hydrogen. The agenda of these workshops is given in pages ii-v and the visual materials presented by the authors are compiled in a CD (located on the inside of the back cover).

Workshop participants made an effort to understand the role of economics and geopolitics as well as the technological shortcomings underscoring some of the resistance to the use of alternate sources of energy within DOD. The workshops were designed to focus on the current and future DOD position, to gain a better understanding of possible responses to energy changes, and to determine what specific recommendations should be made to DOD for dealing with possible future energy crises. The following key questions were posed to the workshop participants and formed the framework for the discussion:

1. What should the Department of Defense do in the near-term to engage with the oil and gas industries as they continue to evaluate future energy sources and production?

2. What role should DOD take on national and international future energy programs? (Either driven by energy shortages or by environmental management concerns).

3. What should be the long-term Department of Defense strategies and policies in regard to future potential energy shortages?

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[3] The Energy Challenge, Special Issue, *Physics Today*, April 2002.

4. What are the current estimates for future availability of hydrocarbon fuels in light of projected global and national demand?

5. What are the economics of supply and demand for alternate fuels and what effect will this have on DOD?

6. What are the environmental constraints, and the legal implications of a hydrocarbon fuel shortage to DOD?

7. Recognizing the wide disparity of opinion on the future availability of petroleum, what is the impact of the extremes of these views on DOD options and possible actions?

This chapter summarizes the views of the participants and speakers at the first workshop in December 2002. Working from notes and tapes of the workshop, the organizers have condensed extensive presentations and follow-on discussions to capture the essential elements of each speaker's arguments. In order to provide the reader with a unified context as well as a sense of the breadth and scope of the workshop, the summaries are introduced in thematic order and do not follow the chronology of the workshop. In their attempt to abridge the salient thoughts, the organizers acknowledge possible omissions of expressed views and opinions.

Review of Presentations

John Felmy (Chief Economist and Director of the American Petroleum Institute Policy Analysis and Statistics Department) addressed the status of current U.S. energy policy in three parts:

- Do we need energy legislation now?
- What do we need and why?
- What don't we need as part of energy policy?

Felmy believes strongly that the United States does need legislation defining an energy policy primarily because the country is struggling to meet demand for energy and policy could help in this struggle. He views energy policy as a national policy to address U.S. needs.

Felmy stated that a national energy policy must be balanced and must include conservation and energy efficiency guidelines and goals. The policy also must contain guidance on renewable energy and have a plan to increase renewable energy much more quickly than the current business as usual, commercial increases now forecast. Guidance on how to increase conventional energy resources also should be included. In addition, the development of methane hydrates, as a source of energy, including the development of all the technology necessary to potentially exploit this resource, should be addressed.

Additional energy policy specifics Felmy proposed included national Research and Development (R&D) in energy efficiency, conservation, and renewable energy as well as

education for all Americans about energy consumption. In Felmy's view, the United States must: continue to expand the strategic petroleum reserve; develop domestic sources of oil and gas; increase supply line capacity (which is now extremely low and decreasing); and reform the U.S. tax code to stimulate investments so as to achieve all policy goals. Felmy notes that U.S. production of finished fuel products has declined continually since 1970.

However, Felmy pointed out that one of the biggest policies proposed in Congress last year was the Renewable Portfolio Standard, which would mandate that 10% of electricity generation come from renewable sources by 2020. This proposal mandates an increase in the total renewable sources in 2020 from 2.5% to 10% of the total energy consumption. Felmy believes that this brute force approach to increasing renewable sources is a prime example of what *not* to do in energy policy development. In his view, there are many other ways to introduce renewable sources into the United States without mandating unnecessarily restrictive changes like those contained in this proposed law. Felmy further believes we do not need mandates such as Corporate Average Fuel Economy (CAFE), which specifies the average minimum number of miles per gallon each manufacturer's vehicles must achieve.

Because of increasing future costs of energy Felmy believes conservation is very important. At the same time he insists more oil resources need to be developed domestically, in places, for example, like the Alaskan National Wildlife Refuge (ANWR).

Felmy stated the need for a sensible policy on climate change and emphasized that the scientific basis for global warming has not been decided yet. For example, he showed data from 50 year rolling averages of sunspot activity vs. global warming temperatures where the correlation was 0.98. His point was that carbon dioxide increases in the atmosphere might not be the cause of global warming. If this is true, simply stopping the use of fossil fuels like coal will not necessarily stop global warming, but assuredly will cause vast economic upheavals.

Hugh D. Guthrie (Senior Management and Technical Advisor to the Department of Energy National Energy Technology Laboratory) articulated his comments on global perspectives for petroleum based on the following premises:

- For the next 50 years we will remain dependent on fossil fuels.
- Environmental considerations are now a must.
- Energy security is critical.

After articulating his premises, Guthrie stated that the decline curve of deep offshore production is now extremely high, and that projections for the life of new ultra deep wells will be less than three years, all of which translates into a continuing need for new wells. Guthrie emphasized the need for theoretical studies of ocean-based gas hydrates highly tempered with the need for practical approaches, which come with the operation of facilities. In developing a national energy policy, Guthrie believes we must encompass

technology, regulation, and economic incentives. Our common objective is affordable, economically viable, and sustainable energy.

In the development of policy or any course of action, Guthrie argues we must try to determine both the upside potential and the downside risk. According to Guthrie, if DOD decides and then takes action on the premise that the energy problem is going to solve itself, the upside potential is zero while the downside potential may not be having energy available when we need it. Hence, the risk to non-action is quite significant. On the other hand, if DOD takes the action of spending more of its money in investigating and supporting the energy future so important to DOD, the upside potential likely will be very significant, particularly in alternate hydrocarbon resources including hydrates, tar sands and oil shale. Guthrie also emphasized that progress does not occur by accident, but because of the commitment of individuals, and he commended DOD and the organizers of the workshop on this regard. He concluded that he would like to see a number of individuals committed to make something—that could make a lot of difference to our grandchildren—happen.

Robert A. Manning (Senior Counselor, Science and Technology, Department of State) gave a presentation on global perspectives and economic view focused on energy policy and energy trends. Manning feels energy is one place where economics intersects most closely with national security, making energy a critical national issue. In his view, a balanced energy policy should reflect steady economic growth, national security, and environmental factors. These, in turn, should shape tax policy, regulatory regimes, and business incentives. Manning theorized that the Stone Age did not end because the world ran out of stones, and the oil age will not end because the world runs out of oil. The impact of technology, including nanotechnology, is underestimated in Manning's view, and this will impact strongly on our energy future. Also, as a matter of energy security, diversity of supplies is important and will drive the search for new energy sources.

From the standpoint of national security, Manning called attention to the fact that for the last 25 years the growth in transportation demand for oil grew twice as fast in Asia than in the rest of the world. As it now stands, Asia-Pacific countries consume more oil than the United States and import most of their oil from the Persian Gulf. This surge has created an Asia Middle East nexus in energy with very strong political implications. Middle classes in India and China are growing rapidly and paralleling their rise is an increasing demand for energy. How China, India, and Japan perceive energy security could be of immense importance to the United States in terms of national security. A naval arms race between China, India, and Japan over sea-lanes is not improbable, according to Manning, and worldwide energy trends should be monitored for just such reasons.

Manning believes that for the next couple of decades the fuel of choice will be natural gas. He would like to see an energy policy initiative to develop clean coal. Technology, in his view, will continue to play an important part in future energy sources and he would like to see more investment in R&D, particularly in the hydrogen economy.

Donald A. Juckett (Director of Natural Gas and Oil Import and Export Activities in the Office of Fossil Energy, Department of Energy) stated that 25% of oil in all the global oil basins has been recovered already, while in global natural gas basins, the figure is 11%. He focused his presentation on projections for the U.S. energy market up to 2025. According to his projections, the primary source of energy through 2025 will be fossil fuels, with natural gas one of the fastest growing sources. Most of this growth will be used in power generation and most will be imported. In America today the fastest growing source of gas is imports with Canada as the largest supplier.

The other important source is Liquefied Natural Gas (LNG). In 2000, the United States had two LNG operating terminals (Boston and Lake Charles, LA), with more scheduled to come back on line (Cove Point, MD, and Savannah). To fully supply all of these terminals will require 400-500 cargoes in LNG tankers (each just slightly smaller than an aircraft carrier), transiting U.S. waterways or harbors. To keep up with demand, new terminals will be needed, and up to 30 more now are being considered. Thus, from a national energy security standpoint, and an infrastructural requirement standpoint, Juckett concludes that some very interesting issues and problems will have to be addressed, among them security and safety of supplies.

Kenneth Deffeyes (Professor of Geology, Princeton University and author of *Hubbert's Peak*[4]) in his book on the impending world oil shortage predicts world oil production will peak in 2004 and begin an irreversible decline thereafter. At the conference, Deffeyes explained that Dr. M. King Hubbert, the late geophysicist who became a world authority on the estimation of energy resources, predicted, in 1956, that U.S. oil production would peak in 1970 and decline from there. Although initially scoffed at, Hubbert's prediction was within one year of the actual peak. Hubbert made his prediction in spite of several unknowns, including the potential and capability of Alaskan production and loss of U.S. dominance in world production. Deffeyes explained how Hubbert used the bell curve approach because Hubbert had found given oil fields historically followed this trend regardless of size. Neither fixing the price of oil nor changing price of oil seemed to affect the bell curve depletion rate. Hubbert based his example on the fact that the most productive U.S. oil discovery period, the 1930's, although coinciding with one of the lowest price periods in U.S. oil history, still adhered to the bell curve.

Deffeyes reminded the audience that no large (greater than one billion barrel) fields have been discovered in the United States since 1960. He interprets this fact to mean that American oil simply has "run out" and he doesn't believe the economists' explanation that we are waiting for the price to go up before we use improved technology to find more. He mentioned that you have to discover oil before you can produce it and currently a lag time of about 11 years exists between these two operations. While this lag is often the source of false alarms about "running out" of oil, in the case of the United States, Deffeyes finds it to be true. He believes some of the economic markers of impending oil supply problems are already beginning to manifest slowdown.

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[4] Kenneth Deffeyes, *Hubbert's Peak* (New Jersey: Princeton University Press, 2001).

Deffeyes notes that in later work Hubbert modified his equations to include a term for the slow down in growth rate as discovery efforts continue. Using these later equations one can plot cumulative production for a geologically defined oil province vs. annual finding or discovery rate for that oil province and, eventually, obtain a straight-line relationship. Where the straight line intersects the x-axis, the total cumulative amount of oil (including that yet to be recovered) is determined. Deffeyes' final estimate of U.S. oil, including Alaska and offshore, is about 220 billion barrels and his final estimate for world total oil is about 2 trillion barrels.

Deffeyes also mentioned that the equations for oil depletion are the inverse of queuing theory equations, but with the same type of result. As oil production begins to decrease, the production system is "at capacity" and queuing theory predicts a noisy system, i.e., seemingly inexplicable price swings, and other chaotic behavior in the system.

Deffeyes highlighted the implications for DOD if oil shortages occur on a global or U.S. basis. He harkens the 1980's, when, during a "political" oil shortage, DOD operations and training missions were reduced due to the high prices of oil. Thus, Deffeyes joins others in predicting that eventually fuel rationing will occur either by price or by inconvenience (i.e., unavailability). Under either of these rationing schemes, the military will be limited in their allotment of oil.

Deffeyes is troubled that, because of the near term production peak, time is no longer available for research and development to impact the problem. He insists that what can be done should be done. He specifically mentioned exploring much higher fuel efficiency automobiles, wind energy production, increased nuclear energy production, and producing hydrogen from coal. He emphasized that for DOD where liquid fuels are most in demand, coal liquids may be the only near term solution to that shortage. The impending shortage is already a serious and immediate problem and the longer it is ignored, the more difficult the solution will be. As a conclusion, Deffeyes again urged for action to be taken now.

Albert Bartlett (University of Colorado, Professor Emeritus) believes that the greatest problem currently facing the human race is our inability to understand the effects of exponential growth and consumption rates. If a natural resource is being consumed at a steady, fixed, non-zero growth rate each year, this is not a linear, but an exponential consumption. Eventually, all non-renewable resources, including all fossil fuel energy sources, will exhibit this behavior over time as a growing population at a steady rate requires a steady, non-zero growth in energy resources.

Exponential growth from a steady non-zero rate of use also can be illustrated alarmingly by the fact of "doubling time." Simply put, if the percentage rate of annual growth rate is divided into 70, then the number of years to double the demand for a resource is obtained. At a growth rate of 2% for oil energy use, oil usage would double every 35 years. That means we would have to discover during each 35-year period enough oil to equal all the oil consumed in the entire previous history of mankind.

At current growth rates for oil (about 2.5% per year global average) we have about a 28-year doubling time. That means that by 2030 we will have to discover 1 trillion new barrels of oil just to keep up with the steady demand. For the last 10 years, finding rates have averaged about 10 billion barrels per year. Thus, by 2030 we will be about 700 billion barrels short of what we need. The problem will continue to worsen every 28-year period after that.

Bartlett had similar comments to make regarding the use of the massive U.S. reserves of coal. A 1970 era congressional report indicated that at current levels of output and recovery, American coal reserves could be expected to last more than 500 years. Yet Bartlett maintains this is only true if all future use of coal maintains a zero percent growth rate. If we apply even a modest growth rate for use of coal, at about 3% per year, and use current best estimates of recoverable U.S. coal reserves, coal would last only about 90 years until it is depleted completely.

Bartlett recommends that Hubbert type analyses for world oil depletion is the correct way to approach the question of a future oil depletion crisis. He finds that the general answer to an oil production peak falling somewhere around 2010 seems to be a reasonable consensus given current data. He concludes that the input data and the calculations should be checked and corrected constantly. Economists and politicians can speculate on this subject , but they must also be checked on a regular basis to ensure they are using the facts and using them in a reasonable manner.

Bartlett believes DOD should initiate and maintain an independent comprehensive study of alternative fuel sources and support their development where possible for critical future needs.

Michael Lynch (Professor of Political Scientist and Executive Director, Center for International Studies, Massachusetts Institute of Technology) feels the impending oil crisis is exaggerated and the Hubbert depletion curves are not useful. Lynch asserts the Hubbert curve analyses rely heavily on assumptions and unspecified assertions, and do not work in most countries. He sees no reliable evidence of scarcity of energy or oil on a global basis. He stated that OPEC oil reserves data are not reliable, and as early as 1977, many analysts began to predict that there might not be enough oil in the reserves estimates, that the finding rates were not high enough, and that this combination might lead to future oil supply troubles.

Lynch believes the reason for so many incorrect predictions of future oil shortages is that the Ultimately Recoverable Resources (URR) estimates for the world are not really reliable. He further stated that URR is not a measure of total world resources, but rather an estimate of the total recoverable portion of that resource at the current technology level and prices. Lynch notes that the amount of recoverable oil in the URR estimates tends to go up over time. He believes future large discoveries will be made in the Middle East and that the U.S. definition of economically exploitable oil is quite different from the Saudi Arabian definition. In Saudi Arabia, for example, a 100 million barrel oil field

may be deemed unexploitable, simply because it is not immediately adjacent to an existing pipeline.

Lynch affirmed that current estimates of URR oil are all about 2 trillion barrels. But, he added, if you remove the economic and technological constraints, the total amount of oil resources becomes about 8 trillion barrels as a conservative estimate. While he recognizes the amount of oil in the ground is not infinite, he thinks it is very large compared to current and possible future consumption. Lynch stated in addition to conventional oil, other unconventional fossil fuel reserves, such as tar sands and oil shale, etc., need to be considered.

Lynch then discussed why discoveries of oil in the last half of the twentieth century have declined. He stated that the big discoveries were made in the Middle East in the 1950s and 1960s. Markets weakened in the 1970s as the Middle East companies all nationalized, concurrently expelled foreign companies, and cut way back on drilling (i.e., exploration). A combination of a wealth of discoveries and a large total oil pool in the Middle East led the Middle East nationalized companies simply to quit looking for oil, thus leading to a perceived worldwide decline in discoveries.

According to Lynch, discoveries have not dropped but gone up. He cites discovery rates (quoted from DOE/EIA) of about 10 billion barrels per year for the last 10 years of the 20th century.[5] Lynch also stated that many small discoveries of oil add up to quite large numbers when considered cumulatively. Lynch believes oil production ultimately is driven by geology—"you have to find the stuff that is there"—but is dictated by price and cost as significant drivers. As the price of oil increases, it becomes more feasible to spend money to drill and find more. In this case, technology matters because production can increase through improvements in technology. Additionally, Lynch believes politics can influence increases in oil production.

Regarding future R&D, Lynch believes the primary drivers should not be scarcity, but the ability to provide cheaper energy than currently available. As far as future dangers, such as the threat of another oil supply crisis, Lynch believes the real threat would be a collapse of oil revenue in OPEC due to a drastic drop in demand followed by OPEC's withdrawal of their foreign investments. Should this happen, Lynch foresees massive worldwide economic disruption.

During the discussion period, Lynch added that as far as policy was concerned he did not think any was justified or needed for the next 20 years or so, since the doubling time at the current increase of consumption is about 20 to 30 years. He noted that if the problem of oil supply and price on world energy were 50 years away, then you would want to start doing R&D now to be able to come to grips with the eventual problem. But, if the problem of oil supply and price is 20 years away, you need to react quickly and start doing something to address the imminent issues. Thus, he favored doing more research at this time, rather than putting policy in place, since by his reasoning, the eventual problems will occur significantly in excess of 20 years from now.

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[5] International Energy Outlook

Charles Maxwell (Oil/Energy Analyst, Weedon and Company) assured the group Wall Street had no perspective on energy. He went on to add that the media is not interested in energy future because the oil industry is not interested in the future of energy. Thus, neither the people involved, nor the public at large, nor the government appears particularly interested or concerned about the future of energy. To Maxwell's mind the situation is so ominous he hopes for a series of mild energy crises to provide a warning or wake-up call—before a major crisis occurs.

Maxwell expressed concern that the recent global collapse in demand[6] for oil has nothing to do with over-production. He cites this as a problem of the oil industry "under-consuming" and believes the oil industry should be re-investing in their future by expending about 8 to 9% of their annual net income for exploration and production. For decades, their historical re-investment followed this trend. However, for the past 4 to 5 years, the average annual investment in this area has been about 1%. This, he cautions, is failing to prepare for the future. Maxwell believes one possible reason for this lack of re-investment in the future growth of oil industry is that the amount of reserves per well, or per 1000 foot of hole drilled, has been coming down remarkably, thereby discouraging re-investment.

Maxwell predicts a very slow recovery in worldwide oil demand for the near future. Yet, at the same time, he expects new production capability from the Caspian Sea region to continue to increase, leading to false expectations of Russia and the Caspian Sea region as major suppliers of oil to importing nations. Maxwell believes that Russia will rebound to production of only about 10 million barrels per day (BPD) by about 2010. This would be an increase from 2002 of 7.6 million BPD. Total future production is anticipated to be 12 to 15 billion barrels in that region. Despite this, Maxwell predicts that the non-OPEC world, including the Caspian Sea region, will reach a peak in production before 2010. After that time, OPEC will become much stronger and U.S. reliance on OPEC supplies will increase.

Maxwell states that with the world currently consuming 27 billion barrels of oil per year, even immense discoveries and exploitation in the Caspian Sea regions would only supply the world for 6 months. Hypothetically, if the world had 50 years of uninterrupted supply of oil, and therefore had the needed time to develop alternate energy sources to replace the projected oil demand in 2050 (assuming no major global economic disruptions during these 50 years), then Maxwell asserts an energy crisis could be averted safely. However, in reality, he is convinced the world has at most ten years (till 2012), before the issues on energy supply and demand become so intense that military and political power will need to be exerted, particularly in the Middle East, in order to abate the energy crisis temporarily. He foresees rationing by price after that point.

Maxwell concluded by warning that the rapid change of investment from a very low energy cost society to a relatively higher energy cost society, in a matter of 3 or 4 years, would create a massive global economic depression.

[6] Ibid.

Edgard H. Habib (Chief Economist, Chevron Texaco Corporation) made little reference to DOD and national policy, nor did he address any of the concerns presented in the opening premise of this paper. Instead, he stated his views as an energy economist, addressing political issues, including the politics of war. He believes that in the United States between 1996 and 2000 we lived beyond our means and consequently this led to a subsequent reduction in our rate of growth. Worldwide, especially in Europe and Japan, growth has been flat or minimal, while Latin America is in trouble economically. This makes the overall market very nervous and easily impacted by terrorism, especially from Iraq and the Middle East.

In the oil market, OPEC controls the floor, while the non-OPEC countries control the ceiling, which, in practice, according to Habib, leads to instability. As an example, he uses Iraq where 96% of national income is derived from oil, making it a political commodity. According to Habib, a long conflict in Iraq could destabilize the whole region. Meanwhile, key Latin American oil producing countries are approaching economic depression, which has serious negative impact in oil supply. Also OPEC market share is dwindling, thereby impacting Saudi Arabian economic leadership in the region. While Saudi Arabia has a national treasury cushion of $180 billion, that may not be enough. Habib stresses that single commodity economies such as those in the Middle East and Africa have to sell oil to survive. However, with OPEC as the price maker in Asia and the Atlantic Basins, a delicate balancing act is required. All of this creates the potential for global instability. Habib concluded that the current global situation in oil-producing countries was tenuous and required watching because of the political and economic linkage of energy stores.

Richard E. Smalley (Professor of Chemistry, Rice University and Nobel Laureate, 1996) began his presentation by listing humanities' top problems for the next fifty years and relating these problems to their dependency on energy. In descending order of importance, Smalley considers the top ten problems to be: energy, water, food, environment, poverty, terrorism and war, disease, education, democracy, and expanding global population (in 2003, world population stands about 6.3 billion; by 2050, it is estimated to reach 9 to 10 billion). From his list Smalley hypothesized that energy is the most important topic and the biggest challenge faced by humanity today. For worldwide peace and prosperity, he believes energy has to be available at low-cost. He noted that—at a minimum—we need 10 Terawatts (10^{15} watts or 6 billion of gallons of oil equivalent/day) from some new clean energy source by the year 2050. Yet current technology will not be able to provide this amount of energy.

Smalley pointed out that the problem of energy provides a great opportunity to enlist Americans in the interest of science and technology for the good of mankind. He equated the magnitude of this challenge to the one presented to the American public in the late 1950s following the launch of Sputnik. Smalley hoped that the American people would respond to this challenge in the way they responded to the Sputnik challenge and that national efforts might attract boys and girls to enter physical science and engineering. In

today's terminology of one-liners, Smalley posits, BE A SCIENTIST—SAVE THE WORLD!

Dr. Smalley called for a bold new Apollo-like program to find new energy technology[7] [8] and emphasized that we can solve this problem with revolutionary breakthroughs at the frontier of physical science and engineering, particularly utilizing nanotechnology approaches. But to do this, a major new federal program on the size of the Apollo project or the Manhattan project is required. Success in this project, like success in the Apollo and Manhattan projects, could revolutionize the largest industry in the world—the energy industry. American boys and girls will enter physical sciences inspired by their idealism, their sense of mission, and their desire to be “where the action is." In this process, the new Apollo or Manhattan energy projects will produce a cornucopia of new technologies and provide the underpinning for vast new economic prosperity for the United States and the world.

James Watkins (former Chief of Naval Operations and Secretary of Energy) covered many areas of energy policy and by way of example discussed the safety record (no nuclear accidents) of Navy nuclear-powered ships, declaring them a national treasure. During his presentation, he focused mainly on the political concerns and difficulties of getting an agreement in Washington among the Administration, Congress, and other groups of lobbyists, who Watkins referred to as "reality." Watkins emphasized how difficult it was to get these groups to agree and to maintain an agreement over the period of time necessary for long-term policy to take hold. He also stressed the problems inherent in dealing with a change in Administration and noted the difference between a military change of command and an Administration change. In the military change of command, both the outgoing commander and the incoming commander want each other to succeed, resulting in a smooth transition in policy and process. In contrast, Watkins finds political administration changes often are marked by the opposite attitudes. Frequently, the incoming Administration believes anything the previous Administration had started is wrong. They immediately try to start over, throwing out the on-going programs and actions of the previous Administration and instituting their own. Very often, over time, the new Administration regresses to the previous points of view. Watkins noted that this happened during his term as Secretary of Energy under the first Bush Administration. He also noted that as the Clinton administration matured, it returned to basically the same policies concerning energy, which he had helped to formulate.

Watkins endorsed the points raised by the fellow participants in the workshop, namely, that energy is a major problem facing the world. He, too, agreed that both the availability and the future use of energy greatly impacts the many problems faced by the world, including hunger, water, poverty, health, etc. In Watkins’ view, these most important challenges ought to be dealt with as scientific and technological opportunities. Watkins urged the assembly to take this opportunity to attract American students to science and technology for the benefit of all mankind.

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[7] M. I. Hoffert, et al, Science, Vol. 298, November 2002.
[8] E. J. Moniz and M. A. Kenderdine, *Physics Today*, April 2002, pg. 40.

Chapter 2

BIOMASS: A FEEDSTOCK WITH GROWTH POTENTIAL

Robert Armstrong

Definition

Biomass is widely discussed as an alternative fuel source. Ironically, it is one of our oldest energy sources, having been used by /mankind ever since we mastered fire. In fact, it ranks as the world's fourth largest energy source, providing about 47 quads of energy annually.[9] There are many arguments in its favor—and in some circles, an equal number of counter-arguments. To gain a full appreciation of the arguments on both sides, it is good to start at the beginning and review some of the basic science involved with biomass energy production.

Simply stated, biomass is vegetation and the various products and coproducts derived from it. Domestically, we recognize four sources of biomass for producing energy: agricultural waste, forestry waste, municipal solid and industrial waste, and energy crops, i.e., crops grown specifically for fuel. The energy content of these sources is energy stored from plant photosynthesis, where plants convert solar energy into biochemical energy.

Biomass can be used in a number of ways as an energy source. The National Renewable Energy Laboratory of the Department of Energy lists the following goals for biomass use by the year 2020[10]:

- 10 percent of transportation fuels
- 5 percent of electric power production
- 18 percent of targeted chemicals and materials

Power generation and chemicals/materials have large constituencies and add significantly to the debate of pros and cons for biomass. (For example, the environmental community hotly debates the use of certain terms related to power generation. They argue that most of the biomass wastes/fuels contain chlorine or other halogens that will produce toxins—dioxins and furans—when burned.) While it is likely that industrial chemicals and

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[9] Cynthia Riley, "Biomass Energy: Economics of Implementing Renewable Energy Resources," presentation given at "Future Energy Resources" symposium, National Defense University, May 7, 2003. (one quad = 10E15 Btu -one quad is the energy in a football field 3.7 miles high filled with oil. Oil is our number one source, providing about 110 quads.)

[10] Ibid.

materials derived from biomass will have a role to play in matters relevant to the Department of Defense (DOD), it is the use of ethanol—derived from biomass—that has the most immediate and near-term importance to DOD. (Ethanol can be used in military operations as a vehicle fuel, as well as a fuel for generators to provide power.) This chapter will primarily focus on the technical and policy issues central to ethanol production and use.

Biomass provides four sources for conversion to energy:

- Simple, or monomeric sugars. These are sugars, such as glucose, that consist of one basic building block. (In the case of glucose, for example, it is exists in one of two forms—either a straight chain or a ring of six carbon atoms, with accompanying hydrogen and oxygen.) Glucose can be fermented to produce ethanol.
- Starch. Starch is a polymer of glucose molecules, i.e., a string of glucose molecules strung together by chemical linkages between adjacent glucose molecules. These linkages can be broken, providing glucose as a source of sugar for fermentation to ethanol.
- Cellulose. Cellulose is the most common form of carbon in biomass and like starch, is made from a string of glucose molecules. The linkages between the adjoining glucose molecules are different from those found in starch, however. The linkages in cellulose cause the material to form highly stable linear chains that are fairly resistant to chemical attack.
- Hemicellulose. Hemicellulose has short, highly branched chains of sugars. In the case of hemicellulose, there are a variety of sugars that comprise the chains. Some of the sugars have five carbons—known as pentoses—and some have six carbon atoms—known as hexoses. Because it is branched, hemicellulose is easy to break into its constituent sugars, which are then available for fermentation—although the pentoses, which comprise the majority of the sugars, are not readily fermentable to alcohol.

Lignin, another component of biomass, is present as 15-30 percent by weight in any lignocellulosic biomass. It combines with hemicellulose to form a protective sheath around the cellulose, and this sheath must be removed before any chemistry can be performed on the cellulose. Even after successful removal and fermentation of the cellulosic and hemicellulosic sugars, lignin remains as a residue. (Lignin does not contain any sulfur and is consequently called "clean coal," as it is the ancestor of coal. Lignin can be used to provide heat and/or power for the manufacture of ethanol from biomass, but to improve the economics of the process, there is considerable research underway to convert it to higher value fuel additives.)

Ethanol

The easiest way to make ethanol from biomass is to ferment simple sugars. Sugarcane and sugar beets are good candidates for this. Historically, through the 1930s, such simple sugars were used to produce industrial grade ethanol. However, due to various

agricultural policies, the price of such sugars is now too high to make it economical to use them.

Industrial production of ethanol production in the United States takes place principally in the Midwest, with the major feedstock being corn. The grain—*not* the biomass materials from the leaves, shoots, roots and cobs (collectively known as “stover”)—is the primary source of the ethanol, with the corn starches—amylose and amylopectin—being converted to sugars that are then fermented. Archer Daniels Midland (ADM) and Williams BioEnergy account for nearly one-half of the nation’s supply at facilities in Illinois. A simplified account of ethanol production involves the following steps:

- Mechanical grinding of the corn to a fine state
- Creation of a slurry through addition of water and an enzyme
- Addition of heat and other enzymes to convert starch to complex sugars
- Conversion to simple sugars through cooling and addition of other enzymes
- Conversion of sugars to ethanol through fermentation via yeast
- Removal of ethanol from the fermented mash, via distillation or evaporation[11]

The biggest debate in current ethanol production methods centers on the use of grain as the feedstock. The essence of the debate is that more energy goes into producing the ethanol—growing the corn, harvesting it, transporting it, and manufacturing the ethanol—than is obtained from it. Since the mid-1970s, the energy balance question has been framed by economists and environmentalists as the calculation of ethanol’s net energy value (NEV), defined as the energy content of ethanol minus fossil energy used to produce ethanol.

Table 1 provides a concise summary of the calculated NEV from a number of studies spanning more than a decade. (Table 1.) Net Energy Value for Ethanol Production based on conversion of corn starches from grain (Adapted from Shapouri.[12])

Study/Year	Net Energy Value (Btu/gal)
Ho (1989)	-4,000
Marland & Turhollow (1990)	18,154
Pimentel (1991)	-33,517
Keeney & DeLuca (1992)	-8,438
Shapouri et al. (1995)	16,193
Lorenz & Morris (1995)	30,589
Wang et al. (1999)	22,500
Agri. & Agri-Food Canada (1999)	29,826
Pimentel (2001)	-33,562
Shapouri et al. (2002)	21,105

[11] “Ethanol and How It Is Made,” accessed at <http://www.klprocess.com/sciofethanol.htm>.
[12] Hosein Shapouri, et al., “The Energy Balance of Corn Ethanol: An Update,” U.S. Department of Agriculture, Office of the Chief Economist, Office of Energy Policy and New Uses, Agricultural Economic Report No. 814, July 2002, 2.

The disparity between the extremes of the studies in table 1 are best explained by differences in the assumptions about corn yields, ethanol conversion technologies, fertilizer manufacturing efficiency, fertilizer application rates, co product evaluation, and the number of energy inputs included in the calculations.[13] Sharp differences exist about these assumptions. During the biomass portion of the National Defense University's symposium on Future Energy Resources, there was intense academic debate between supporters of the assumptions used in Pimentel's 2001 study, vs. those used by Shapouri et al. in their 2002 assessment. As is evident from the respective NEVs in the two studies, there is considerable disagreement about the economic and environmental sensibility of manufacturing ethanol from grain. (It should be noted, however, that the Shapouri study represents a Federal government study and will most likely be used to support further government programs.)

Definitions of commonly used terms related to alternative fuel

Biofuels—a term generally used for liquid fuels for transportation, although it can refer to fuels for direct combustion or electricity production

Bioethanol—ethanol made from cellulosic biomass materials instead of traditional feedstocks (starch crops)

Renewable diesel—fuels used in diesel engines in place of or blended with petroleum diesel, but made from renewable sources such as vegetable oils, animals fats, or biomass

E-diesel—a blend of ethanol and diesel fuel (in addition to other chemicals to improve performance). The ethanol portion of E-diesel is made from renewable sources, such as biomass.

Fischer-Tropsch diesel fuel—diesel made from coal and natural gas today, but eventually may be made from any organic material, including biomass

Biodiesel—diesel fuel made from animal fat or vegetable oil (can be blended with conventional diesel fuel or used as a neat fuel, i.e., 100% biodiesel)

Gasohol—fuel ethanol

E-10, E-85, etc.—a blend of petroleum and ethanol. The number following the "E" indicates the percentage of ethanol in the blend.

Soy diesel—diesel fuel made from soybean oil, noted for its distinctive "French fries" smell

[13] Ibid., 3.

There is little disagreement, however, about the ultimate goal of economically producing ethanol from agricultural and forestry wastes, as well as from crops grown specifically for such purposes. Lignocellulosic biomass costs between \$30–60 per ton.[14] Corn costs about \$77 per ton (\$2.15 / bushel). The real difficulty is in our ability to economically convert the lignocellulosic materials to simple sugars that can be fermented. (Clearly, the current debate about NEV will become moot, once economic methods of lignocellulosic conversion are developed.)

The relative amounts of cellulose: hemicellulose actually depends upon the plant species and age, although cellulose is always the majority constituent. In general, hemicellulose comprises about 20 percent of any given quantity of lignocellulosic material. The preparation/separation of the lignocellulosic material is an expensive and difficult process. In addition, the pentoses obtained from hemicellulose present another technical challenge, as they are not easily converted to ethanol.

One reason agricultural and forestry wastes make ideal candidates for ethanol production is their abundance. Corn stover alone could provide 120 million dry tons of biomass. Wheat straw could provide close to another 100 million tons. At present, some agricultural wastes are deliberately left in the field for soil conservation purposes, and those practices are likely to continue. Historically, however, much of the agricultural waste has been burned. That option is being eliminated in more and more jurisdictions, though, because of air pollution considerations. Thus, converting it to ethanol would not only solve the waste problem, but also provide a value-added option for its disposal.

The discussions of forestry management that have been in the news in recent years also have direct bearing on the issue of ethanol production. Forestry wastes include underutilized wood and logging residues, imperfect commercial trees, and non-commercial trees that need thinning from fire-prone stands. Such material could provide nearly 300 million tons of biomass annually.

Energy crops have also been an area of active research for several years. Some estimates suggest about 100 million acres of land could be available annually specifically for energy crop production. Such land would not compete with land needed for more traditional agricultural uses. Actually, farmers could use their marginal land for such crops. Fast-growing trees, shrubs, and grasses are good candidates for energy crops. Much work has already been done with hybrid poplars, willows, and switchgrass. (Energy crops are also attractive from a farm economics perspective, as they provide the farmer with a stabilizing hedge against the vagaries of the commodities markets.)

With all of these readily available feedstocks, supply of raw materials is not the problem in ethanol production. The development of more efficient technologies—especially improved enzymes--for the conversion of lignocellulosics is key to making these

[14] All prices in this report are as of the time of the workshop.

materials economically viable.[15] Currently, with the enzymes presently used to facilitate the pretreatment of biomass and the subsequent fermentation of the sugars, a gallon of ethanol costs about $2.30 to produce. Plans for the first commercial scale biorefinery using more efficient, genetically modified enzymes, call for a $1.22 per gallon target price. Ultimately, by 2050, bulk fuel production techniques project a $.75 per gallon target price.[16]

Table 2. Gasoline Gallon Equivalent (GGE) Table[17]

Fuel Type	Unit of Measure	BTUs Per Unit	Gallon Equivalent
Gasoline, regular unleaded, (typical)	Gallon	114,100	1.00 gallon
Gasoline, reformulated (10% MBTE)	Gallon	112,000	1.02 gallons
Diesel, (typical)	Gallon	129,800	0.88 gallons
Methanol (M-100)	Gallon	56,800	2.01 gallons
Methanol (M-85)	Gallon	65,400	1.74 gallons
Ethanol (E-100)	Gallon	76,100	1.50 gallons
Ethanol (E-85)	Gallon	81,800	1.40 gallons
Biodiesel (B-20)	Gallon	129,500	0.88 gallons

The concept of gasoline gallon equivalent (GGE) allows for the comparison of cost of fuels and mileage. For example, it can be seen from table 2 that to obtain the same amount of energy as is contained in one gallon of regular unleaded gasoline would require 1.4 gallons of a 15% blend of ethanol (E-85). Thus, to travel a given distance, it would take 40% more E-85 than regular unleaded gasoline.

Aside from the benefits of using domestic feedstocks and the economic advantages ethanol production may bring to the farm sector, supporters also point to ethanol's environmental advantage. Typically, two benefits are cited: the reduction in ground level ozone and the reduction in greenhouse gases.

Ground level ozone results from the interaction of vehicle exhaust and sunlight. It is a serious environmental pollutant, causing respiratory problems, as well as being injurious to various plants. Unfortunately, the production of ground level ozone does nothing to contribute to the lack of stratospheric ozone. Ethanol is not as volatile as gasoline and helps reduce the production of ground level ozone, according to proponents.

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[15] Riley. An interesting historical footnote to the search for enzymes involves U.S. forces in WWII. Men serving in the Pacific were having problems with the disintegration of their clothing and canvas equipment. An organism living in the canopy of the tropical rainforest was excreting an enzyme that broke down cellulose. The enzyme was raining down on the troops and their equipment and causing the disintegration. That enzyme is currently used in the production of Stonewash jeans.

[16] Riley.

[17] "What is a GGE?" Alternative Fuels Data Center FAQs, accessed at <http://www.afdc.nrel.gov/p_single_faq.cgi?5>.

The so-called Greenhouse Gases—gases contributing to the earth's warming—include carbon dioxide, methane, and nitrous oxide. These gases are all components of vehicle exhaust. According to some sources, the use of ethanol blends can reduce their levels by about 37 percent. In fact, it is argued that more carbon dioxide is absorbed by plant growth, than is generated by the manufacture and use of ethanol. Carbon monoxide emissions in vehicle exhaust also contribute to air pollution and are of particular concern when vehicles are operating at lower temperatures. Oxygenated gasolines, such as ethanol blends, lower the levels of CO emitted, by promoting a more complete combustion of the fuel.[18]

Just as the NEV discussion reveals opposing camps, there are differing opinions about the environmental effects of using ethanol. Patzek and others--including a 1999 blue ribbon panel for the Environmental Protection Agency—state that ethanol contributes pollutants to the air. Although they concur that it can decrease carbon monoxide, they argue that ethanol's volatility means that it can increase volatile organic compounds—VOCs—when burned. They argue that the VOCs, along with other chemicals, including nitrogen oxides and aldehydes, are precursors to ground ozone and actually contribute to the problem.[19] (Patzek also contributes to the NEV debate and concludes that "as much fossil energy is used to produce corn ethanol as can be gained from it.")

With economic and environmental arguments on both sides, what then is the current state of ethanol? Presently, the industry is approaching the 2.7 billion-gallon/year mark, based primarily on cornstarch. It is used mostly as an oxygenate, to curb seasonal environmental problems associated with standard gasoline.[20] Depending upon the time of year and the location in the country, a tank of gas purchased by an average consumer may or may not be blended with ethanol.

The industry recently received a tremendous boost, however, with the move to ban MTBE—methyl tertiary butyl ether—as an oxygenate. MTBE has been used for some time as an oxygenate—to allow for more complete burning of the gasoline and a reduction in pollutants—and is actually preferred over ethanol. MTBE blends more easily with gasoline and it is less expensive than ethanol. However, MTBE has been found to be leaking into some water supplies. It has an unpleasant taste, as well as being a potential carcinogen. The unpleasant taste is present at levels even lower than those considered potentially threatening to human health. In California, MTBE is to be removed as an oxygenate from fuels by the end of this year.

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[18] "Green Fuel: Biotechnology for Clean Energy," accessed at <http://www.greenfuelonoline.com>.

[19] Ted Patzek, "Ethanol From Corn: Clean Renewable Fuel for the Future, or Drain on Our Resources and Pockets?" Working paper, University of California-Berkeley, June 2003.

[20] Alcohols and ethers are the primary oxygenates used for gasoline. Ethanol is the most commonly used alcohol and MTBE is the most commonly used ether.

(Obviously, such a dramatic change in the role of ethanol has significant political implications, given the power of the Midwestern farm lobby. While it is not the role of this chapter to explore all of the political implications associated with ethanol and its production, the reader should be aware that the issue of ethanol production is not just a topic of scientific or technical debate and that policy decisions made about ethanol may likely have a large political component.)

The Future

It is understandable that much of the current biomass discussion focuses on ethanol production and the various economic, environment and political debates associated with it. As noted from the discussion above, most of current day ethanol production really is not from biomass, but from grain. Until the economics of the enzymatic treatment of lignocellulosics improves, that is likely to continue to be the case.

Much talk has been heard recently about the hydrogen economy, in which hydrogen becomes our primary energy source. That seems in stark contrast to the discussions of the biobased economy that have emerged of late, with biomass playing a prominent role as a feedstock for energy.[21] Actually, the hydrogen economy and the biobased economy are quite compatible. Biomass may be a source of hydrogen—which can then be used for energy. Much more than energy, however, will come from the other bioproducts derived from both plants and animals in a biobased economy.

With biorefineries replacing the more familiar petroleum refinery, biomass will be used as a feedstock. For ethanol production, the feedstock could enter the refinery, go through the pretreatment, enzymatic hydrolysis of cellulose and sugar fermentation, as described earlier in this chapter. The end product would be ethanol, or other bioproducts. Just as probable, though, is a biorefinery that takes biomass and through completely different processes produces hydrogen, which is then used for energy.

The biomass production of hydrogen is an active area of research. In general, there are two basic approaches: the direct production of hydrogen from biomass; or, the conversion of stable intermediates. The direct route's advantage is its simplicity. However, because of storage and transportation issues involved with direct production, the conversion of intermediates has its advantages. Specifically, the production of the intermediates can be geographically distributed, thus reducing the transportation costs of the biomass.[22]

Both approaches—either direct production or production of intermediates—have a number of different technologies that can be classed as either thermochemical or biological routes. Currently, the four technological approaches that are the most mature are: indirectly-heated gasification; oxygen-blown gasification; pyrolysis; and biological gasification (anaerobic digestion). In general, regardless of the process used, the yield of

[21] Robert E. Armstrong, "From Petro to Agro: Seeds of a New Economy," accessed at <http://www.ndu.edu/inss/DefHor/DH20/DH_20.pdf>.
[22] Thomas A. Milne, et al., "Hydrogen from Biomass—State of the Art and Research Challenges," accessed at <http://www.eere.energy.gov/hydrogenandfuelcells/hydrogen/iea/pdfs/hydrogen_biomass.pdf>.

hydrogen from biomass is low, because the hydrogen content of biomass is low to begin with—e.g., six percent hydrogen content for biomass, vs. 25 percent for methanol. In fact, about half of the hydrogen from biomass—regardless of production method--comes from splitting water apart during a procedure known as “steam reforming”—in which steam is passed over a catalyst in the presence of the biomass to produce hydrogen and carbon oxides. (Without high-value co-products from the biomass, the current production costs do not make it economically competitive with hydrogen production from natural gas.)

Obviously, the economics of production are a function of the process used, but it must be remembered that none of these platforms are as well developed as the fermentation process for sugars. Work by Danz suggests that production costs—using either gasification techniques or pyrolysis techniques—can be reduced by nearly three-fourths during the next five to ten years.[23] Moreover, environmental analysis suggests that hydrogen from biomass will emit fewer greenhouse gases than hydrogen from natural gas—1.4 carbon dioxide equivalents per 1 kilogram of hydrogen product for biomass hydrogen, vs. 11.9 for natural gas. Thus, biomass may yet become a viable source of energy.[24]

Biomass at DOD

While our long-term interest may be in energy security for the nation, the immediate needs of DOD should be of concern. During the recent action in Iraq, for example, it is estimated that the cost of one gallon of fuel delivered on the battlefield was approximately $300.[25] Even an imperfect production method that was not economically viable in the civilian sector would be of benefit—at those prices, even $200/gallon ethanol would represent a huge savings!

Fuel is the Army’s second largest logistical demand on the battlefield. (See figure 1.) To help reduce the logistical requirements of moving all of that fuel to the battlefield, there is a need for a small—able to fit inside a military cargo plane—biomass to ethanol production facility. Such a facility could manufacture ethanol from available biomass in a given military theater. For areas where there may be insufficient biomass available—Saudi Arabia, for example—biomass could be stockpiled nearby.

To ensure a fuel supply in Saudi Arabia, for example, farmers in the Horn of Africa could be contracted to grow energy crops that could then be stockpiled in strategic areas, based on warplans for the region. Growing such crops under contract would bring economic development to the region. In fact, in such areas where fuel is expensive and scarce in the first place, the sale of such ethanol production facilities that could use locally grown crops could spark tremendous economic growth. In addition, our military would have a readily available and easily managed strategic fuel reserve in the region.

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[23] Roxanne Danz, “Biological- and Biomass-Based Hydrogen Production, accessed at <http://www.eere.energy.gov/hydrogenandfuelcells/hydrogen/pdfs/danz_biomass.pdf>.
[24] Riley.
[25] Jerry Warner, COL, USA (ret.), personal communication.

Although diesel fuel is still used in some applications, the Army is moving towards the use of JP-8 for all fuel needs--including aircraft, tanks, vehicles, generators, etc. (JP-8 is one of the family of Jet Propulsion fuels. Essentially, it is kerosene and is widely used in military and civilian aviation.) Logistically, this makes sense, in that it simplifies the fuel issue and avoids the potential of mixing fuels and having to have separate distribution systems. However, recent studies indicate that stationary assets--food preparation areas, operations centers, medical facilities, for example--are the biggest consumers of fuel in land based military operations.[26] Food waste from mess halls and packing materials from depot operations are just two possible sources of feedstocks that could be used to produce ethanol, which in turn could be used as fuel for generators in these various stationary sites. The utility of such small ethanol production facilities on board ships is obvious.

Policy Decisions

Obviously, doing something as dramatic as changing fuel supplies—even keeping petroleum as the main fuel supply and augmenting it with biomass produced ethanol—will not happen without considerable political impetus and public policy. In a recently published policy document, the Energy Future Coalition—a bipartisan group making recommendations for energy policy changes—examined various areas of our energy situation. Their overall focus was the energy security of the nation and as part of their proposal, they called for the pursuit of biomass programs.

Most interesting, however, was their recommendation specific to the Department of Defense:

> The Department of Defense (DOD) should be authorized and directed to conduct a one-time procurement "fly-off," with the objective of building 5 to 10 commercial-scale demonstration plants with 5 years. The purpose should be to test the viability of various novel conversion processes applicable to diverse and abundant feedstocks, producing different end products—e.g., ethanol, syngas, chemicals, electricity, hydrogen, and other bio-based products, even gasoline…A one-time appropriation of $1 billion should be provided to carry out the competition, and DOD should be given wide latitude to disburse those funds for maximum impact…Within a short time, the fly-off would prove whether America's farmers and foresters can grow our way out of the continuing "energy crisis" and bring substantial environmental benefits as well.[27]

It is not just domestic policy, either, that needs review, if we are to use biomass in a meaningful way for the production of fuels and other resources. In a recent piece, three prominent former government officials—again, a bipartisan group—called for the elimination of farm subsidies.[28] In their view, such subsidies are a stumbling block that

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[26] Ibid.

[27] "Bioenergy and Agriculture," in "Challenge and Opportunity: Charting a New Energy Future, June 2003, accessed at <http:www.energyfuturecoalition.org/full_report/app_bio_agric.pdf>.

[28] Timothy E. Wirth, et al., "The Future of Energy Policy," *Foreign Affairs*, vol. 82, no. 4 (July/August 2003), 132-155.

not only threaten the success of the current Doha Round of trade negotiations, but also are an impediment to the development of the biomass fuel industry on a worldwide scale.

Citing World Bank studies, they note that annually $300 billion of subsidies are paid in industrial countries for agricultural products. They argue that such subsidies undermine developing-world exports. In fact, they point out that the total of such subsidies is about six times greater than current development assistance payments. Specifically, with respect to lifting such subsidies in industrialized countries, they again cite a World Bank study that predicts such action would increase global agricultural trade by 17 percent and raise agricultural and food exports from low- and middle-income nations by 24 percent.

The argument is that as the developing countries become self-sufficient in agriculture, their farmers will be able to include industrial and energy crops in their mix. In summary, they conclude that "shifting farm export subsidies to support biomass fuels would encourage the production and reduce the costs of agriculturally derived petroleum substitutes, while also breaking down distortions in world markets and barriers to trade for farmers in developing countries."

(It is important to note, parenthetically, that not everyone agrees with this view of the potential net result to be derived from ending farm subsidies.[29] An alternative expressed in a recent NY Times editorial holds that ending subsidies will make third world agricultural areas attractive to multinational agribusinesses that use modern farming techniques. The ability to grow more on less land—the hallmark of first world agriculture—will benefit third world wilderness by saving it from the plow. However, it will have the same effect on third world agrarian populations as it did in the first world—the need for farm labor will be reduced quickly and dramatically, causing societal disruptions. Even given this disadvantage, the author noted that first world subsidies should be reduced. In his view, they are an anachronism from another era, when they were needed to help create a rural middle class, when much of the population was engaged in agricultural production. Even though the end results differ from those expressed above, it is interesting to note that there is agreement that the subsidies should be reduced, if not ended.)

Thus, biomass is not just about U.S. farm policy. It is not just about U.S. energy independence. It is not just about reducing the logistical tail for U.S. military operations. Developing biomass as a source of raw materials for various industrial uses—including fuels—has global implications, both economic and environmental. There is no shortage of sound advice to policymakers. Bipartisan action—aimed at all of the factors involved: farm policy; energy policy; military operations; global trade—is needed, and needed soon, to insure we take full advantage of our technological abilities and agricultural bounty.

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[29] Commentary, "The Cancun Delusion," *The New York Times*, Friday, September 12, 2003.

Chapter 3

HYDROGEN AS A FUTURE ENERGY RESOURCE

Timothy Coffey, Jill Dahlburg, and Dennis Hardy

DOD Perspective

Few matters impact defense planning as much as energy. There are two primary reasons for the importance of energy considerations. Recent circumstances provide testimony to the first, which is the potential employment of the military forces to ensure the continued movement of world supplies of energy resources, for example oil. The second reason is that DOD is itself a large consumer of commercially produced energy, and market attributes such as energy supply and fluctuations in price can have a significant impact on the ability of DOD to accomplish its missions. The nature of the energy source is also quite important to the Defense Department. This has been and continues to be true, especially in the case of hydrogen as a source of fuel. Given the stake DOD has in energy, it is imperative that DOD remains engaged in the debate and process towards alternate fuels.

DOD interest in hydrogen as an energy storage medium goes back at least to 1944, when the Navy Bureau of Aeronautics began to consider seriously the prospects of putting artificial spacecraft in orbit. Some of the then-funded activities included hydrogen fuel rockets, from which DOD collected a considerable amount of test data. In the 1950's, the decision was made to proceed with the development of the hydrogen bomb. Out of the substantial influx of related defense resources during this time came much of the technology which the world depends on today for liquefaction as well as tremendous advances in cryogenic engineering. During this period, the Air Force and the National Advisory Committee for Aeronautics ran a series of hydrogen-powered aircraft programs. While the work on these aircraft came to a close with the launch of Sputnik, the facilities developed during this work were key to the subsequent space program.

The 1950's hydrogen aircraft designs and the hydrogen-related issues defined during and following that period[30] remain highly relevant with respect to DOD missions and the role of hydrogen therein. For primarily fuel-oil powered military platforms like ships and aircraft, conversion to either liquid or compressed gaseous hydrogen would require four times the current fuel volume in order to achieve the same mission. Even if the expected progress in fuel cells improves, the situation with regard to storage and the safety issues associated with cryogenic liquid or very high pressure gaseous hydrogen will persist.

[30] H.W. Carhart, W. A. Affens, B. D. Boss, R. N. Hazlett, and S. Schuldiner, "Hydrogen as a Navy Fuel," NRL Report 7754, June 12, 1974.

If the nation decides to go towards a hydrogen economy, DOD is not going to be able to run an independent fuel empire. It will need to assimilate the products of the commercial energy marketplace and, for missions that are compatible with hydrogen, adapt accordingly. For missions incompatible with hydrogen propulsion or hydrogen fueling, DOD will need to develop viable alternatives, such as environmentally acceptable ways to produce the needed hydrocarbon fuels.

Clearly, how DOD responds to a commercial hydrogen economy will depend upon issues like the rate of transition to a hydrogen economy and the ultimate means for the production of hydrogen. In all of these stages and issues substantial technological opportunities are to be found. For example, some of the current battery powered equipment used by DOD would perform better if they were hydrogen powered. In the process of movement towards the hydrogen economy, the overall impact on DOD—which will be substantial—must be kept in mind. Equally imperative, DOD needs to remain engaged in this process.

Review of Presentations

This report presents a summary of the Hydrogen Workshop held at the National Defense University (NDU) on May 9, 2003 as part of the NDU workshop series on future energy resources. The workshop brought together a broad spectrum of people with varied interests and expertise regarding the issues associated with moving towards a hydrogen economy. While the move towards a hydrogen economy has been under consideration for more than 25 years,[31] the workshop was especially timely in light of the declaration by President Bush in his State of the Union Address to Congress that he intends to launch a new hydrogen fuel initiative. At the European Union Conference on Hydrogen in June 2003, Energy Secretary Abraham further elucidated this initiative with the announcement that "over the next five years the Department of Energy will invest $1.7 billion in research and development of hydrogen vehicles and hydrogen infrastructure technologies."[32] The magnitude of this transition from both an infrastructure and technological perspective was touched upon in varying ways by all of the workshop speakers and summaries of their arguments follows.

Valri Lightner (U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE)) opened the workshop by stating that today the United States imports 55% of its fuel for transport with that percentage expected to grow to 68% by 2025, as depicted in figure 2. Since transportation accounts for two-thirds of the 20 million barrels of oil consumed by the United States each day, the focus for the future, according to Ms. Lightner should be on reducing oil consumption in the transportation sector. A reduction there would contribute much towards mitigating the dependence on foreign oil and would alleviate the attendant security issues inherent in that dependence.

[31] D. L. Bartlett and J. B. Steele, "The U.S. is Running Out of Energy," Time Magazine, July, 21 2003.
[32] *http://www.energy.gov/engine/content.do?PUBLIC_ID=12760&BT_CODE=PR_PRESSRELEASES&TT_CODE=PRESSRELEASE*

Yet while reducing fuel imports has definite advantages, Ms. Lightner foresees additional measures being necessary, especially with the stated goal of moving the Nation towards a hydrogen economy. To address the multiple concerns associated with fossil fuel depletion and green house gas production, hydrogen has been proposed as a potential energy storage medium. When burned, hydrogen is clean, producing mainly water. While hydrogen does not appear naturally in its elemental form, it is abundant as a constituent of various chemical compounds such as water, coal, and biomass. There are a number of domestically produced energy sources, such as fossil fuels (with carbon capture and sequestration), renewable energy, and nuclear energy, that potentially could be used to separate hydrogen from the chemical compounds in which it is bound. The use of hydrogen to power low temperature polymer electrolyte membrane fuel cells is viewed as a very promising means of converting hydrogen directly to electricity for use by the transportation sector.

DOE is in the process of drafting a hydrogen posture plan to outline the activities, milestones, and deliverables that the Department must pursue to promote America's shift to a hydrogen-based energy system. The DOE strategy constitutes four phases, extending to 2040. Phase I consists of the technology development necessary for hydrogen power and transport systems to be made available in selected locations with limited infrastructure. Phase II deals with an initial market penetration, where hydrogen power and transport systems begin commercialization. In Phase III, large-scale infrastructure investment begins, with hydrogen power and transport systems becoming commercially available. During Phase IV, fully developed markets materialize along with the associated national infrastructure.

In order to effectively accomplish the above strategy and transition to a hydrogen economy, a number of critical path technologies must be pursued. These are associated with increasing performance or efficiency and/or reducing costs in the areas of: compact lightweight hydrogen storage for transportation purposes; hydrogen production; fuel cells, with costs primarily catalyst-driven; and carbon sequestration. The relevant critical path technologies along with the DOE projected performance targets are summarized in Table 3.

Table 3. Critical path technologies for transition to a hydrogen economy.

"Critical Path" Technologies	**Target**
Compact, lightweight hydrogen storage	*Performance increase:* 2-3x
Hydrogen production costs competitive with conventional fuels	*Cost reduction:* 4x
Fuel cell costs competitive w/ conventional engine technologies	*Cost reduction:* 10x
Low cost carbon sequestration	*Cost reduction:* 10x

Ms. Lightner concluded with a discussion of the projected budget requests of different DOE departments and what that heralds for hydrogen development. The fiscal year 2004

request includes collaboration between the Offices of Fossil Fuel, Nuclear Energy, Science and Technology, and Energy Efficiency and Renewable Energy on cost-shared hydrogen production. The Office of Fossil Energy will make a $5M investment in coal-related technologies that addresses the separation of pure hydrogen from synthetic gas. These technologies are also believed to be applicable to biomass feedstock. The Offices of Fossil Energy and of Energy Efficiency and Renewable Energy will make a $12.2M investment aimed at developing small distributed systems that will use natural gas as the feedstock to produce hydrogen. The Office of Nuclear Energy will make a $4M investment looking into high temperature thermochemical cycles for splitting water using nuclear energy as the thermal source. The Office of Energy Efficiency and Renewable Energy will make a $17.3M investment to address hydrogen production by means of a variety of processes, among them direct water splitting using solar energy, thermal processes using biomass, and advanced electrolysis from wind power.

The overall strategic performance goals of DOE are summarized in Table 4.

Table 4. DOE Hydrogen Production Program Strategic Performance Goals.

Program Strategic Performance Goals	**Status**	**Target**
A. H_2 production (natural gas–delivered) *per gallon of gas equivalent (gge) and per kilogram (kg)*	$4.50/gge $1.30/kg	$1.50/gge by 2010 $0.43/kg
B. H_2 production (biomass–plant gate)	$3.60/kg	$2.60/kg by 2008
C. H_2 storage energy density	1.2 kWh/kg 0.65 kWh/l	2.0 kWh/kg by 2010 1.5 kWh/l by 2010
D. Validate integrated H_2 infrastructure project	$4.50/gge	$3.00/gge by 2008
E. Global technology regulation for H_2 fuel cell vehicles and infrastructure	National plan under review	Draft technical specifications by 2007
F. Educate key target audiences on hydrogen	TBD	5% increase by 2008
G. Reduce cost–vehicle fuel cell power systems	$250/kW	$45/kW by 2010
H. Increase electrical efficiency of stationary fuel cell systems (natural gas)	<30%	$\geq$40% by 2010
I. Validate fuel cell performance in systems context	1000 hours durability	2000 hours durability by 2008

Robert Williams (Princeton Environmental Institute) discussed hydrogen production technologies and strategies for large-scale centralized hydrogen production for the long term, which he defined as beyond 2020 or 2030. His focus was on coal gasification and geological sequestration of carbon dioxide. He noted that the main attractions of hydrogen as an energy carrier are its potential for near zero fuel cycle emissions of greenhouse gases as well as zero, or near zero, emission of air pollutants. Near zero greenhouse gas emissions is realizable only through the production of hydrogen from

water via electricity or some other form of heat from a carbon free primary energy source, or through the production of hydrogen from biomass or fossil fuels with carbon dioxide capture and storage. Williams briefly discussed centralizing hydrogen production options, which include: advanced electrolysis via low carbon or zero carbon electricity sources; complex thermochemical cycles using nuclear heat from high-temperature gas cooled reactors; steam reforming of natural gas with underground storage of separated carbon dioxide; and coal gasification with underground storage of separated carbon dioxide. He concluded that coal gasification appeared to be an especially attractive production scenario if the long-term issues connected with carbon dioxide sequestration could be resolved satisfactorily.

Coal is especially attractive as a hydrogen feedstock for the reasons that it is abundant both globally and in the United States and that, since much of the global population is already heavily dependent upon it, extensive coal mining and processing infrastructure is already in place. Further, coal prices tend to be low and nonvolatile. Therefore, coal gasification could be a politically stable alternative to oil for transportation. If large-scale carbon dioxide sequestration is demonstrated, the production of hydrogen via gasification of coal could be accomplished with near zero emission of air pollutants or greenhouse gases. Dr. Williams' analysis indicates that production costs for coal-derived hydrogen with carbon dioxide capture and sequestration could be competitive with the production of hydrogen from natural gas with comparable carbon dioxide sequestration when natural gas prices reach about $4 per gigajoule. Potential challenges to this method are the residual environmental, health, and safety problems associated with the mining of coal.

Coal gasification is a well-understood commercial process that has been providing chemicals to the marketplace since at least 1970. The major issue with respect to coal gasification for the production of hydrogen is the disposal of residual carbon dioxide. There appear to be several prospects to counter this issue. These include deep ocean disposal; disposal in geological media such as depleted oil and gas fields, beds of unmineable coal, or deep saline aquifers; or disposal as carbonate rocks. There is some understanding of the global capacity for carbon dioxide storage in deep saline aquifers. If closed aquifers with structural traps were determined to be required, the disposal capacity would be approximately 50 gigatons of carbon. If large open aquifers with good top seals are usable, estimated storage availability ranges from 2,700 to 13,000 gigatons of carbon. To put the amount of storage required into perspective, the cumulative emissions for fossil fuel burnings from 1990 through 2100 are estimated to be about 1,500 gigatons of carbon, with the carbon content remaining in exportable fossil fuels (excluding methane hydrates) estimated to be between 5,000 and 7,000 gigatons of carbon.

Storing carbon dioxide as a carbonate mineral also has some advantages worth considering. In particular, sufficient resources are available to store all remaining recoverable fossil fuels as carbonates. The disadvantages are that large amounts of material must be transported, processed, and stored. This likely would prove much more costly than disposing of supercritical carbon dioxide in deep saline aquifers, but it is a very safe disposal method.

While Williams feels it is clear hydrogen will not be used widely as an energy carrier for at least 20 to 30 years, he sees near term opportunities for exploiting the hydrogen that is presently produced in chemical refining industries. For instance, gasification based hydrogen production at oil refinery plants and in ammonium nitrate plants might be used as low cost sources of CO_2 for mega scale (on the order of 1M tons) demonstration projects of CO_2 storage in various geological media. Williams noted that it is still unknown whether closed aquifers or open aquifers will be sufficient to store CO_2 for geological times. This question is critical due to the relatively low capacity of the closed aquifers. He argued that it is important to find out as soon as possible if geological storage of carbon dioxide is viable.

Wayne Surdoval (National Energy Technology Laboratory (NETL) in the DOE Office of Fossil Energy) discussed the Solid State Energy Conversion Alliance (SECA), which is a component of the Office of Fossil Energy fuel cell program. The goals of this high temperature fuel cell program are to develop technology that is both low cost and widely applicable, and which will support the climate change and energy security objectives of the administration with respect to moving the Nation towards a hydrogen economy. By the year 2010, the vision for these high temperature fuel cells is to produce low-cost high-volume units at an estimated cost of $400 per kilowatt and with an annual volume exceeding 50,000 units per year. These estimates are considered to be cost-competitive on a distributive generation basis with technology that exists today. It should be noted that the fuel cells mentioned by Surdoval are of a higher temperature than the fuel cells previously discussed by Lightner.

SECA is viewed as a path to making fuel cells a reality. The program is structured to allow for industry input to the Department of Energy, which will then resource the national laboratories, universities, and industries to develop the needed core technology and subsequently transfer that technology back to the industrial teams. Intellectual property is viewed as the cornerstone of the alliance, which is composed of six alliance industry teams: Cummins Power Generation; Delphi/Battelle; General Electric; Siemens/ Westinghouse; FuelCell Energy Inc.; and Acumetrics. The products from the core technology program will be available to the industry teams via nonexclusive licenses. Each of the teams is pursuing different approaches and is charged with meeting the minimum technical requirements shown in Table 5.

Table 5. SECA Minimum Technical Requirements

Cost	$400/ kW
Power Rating Net	3-10 kW
Efficiency (AC or DC/LHV)	30-50% [APU] 40-60% [Stationary]
Fuels (Current infrastructure)	Natural Gas; Gasoline; Diesel
Design Lifetime	5,000 Hours 1,000 Cycles [APU] 40,000 Hours 100 Cycles [Stationary]
Maintenance Interval	> 1,000 Hours

Gregory Keenan (Air Products and Chemicals, Inc.) presented an Air Products and Chemicals perspective on the challenges and opportunities in implementing a hydrogen economy. Keenan stated that one key to using hydrogen as an energy carrier is that it is a very flexible carrier, and as such, is able to be produced in many different ways to meet the individual needs of end users. He noted that while more than 85% of consumers believe it important to decrease U.S. dependence on imported oil, getting those same consumers to favor paying for this transition is a very different and more difficult matter.[33] Yet just as the oil and gas industry infrastructure have been built up over many decades at immense cost, Keenan feels it should be expected that a hydrogen infrastructure would follow similar time lines and costs. The challenges to transition involve issues such as cost, performance, reliability, safety, consumer acceptance, and the development of the approaches for the necessary infrastructure.

Because of the large number of ways of making, transporting, and storing hydrogen, Keenan feels it would be difficult to simply design a one size fits all infrastructure. He argued that the infrastructure for a hydrogen economy would be vastly more diverse than that of oil and gas and that it would be much more responsive to individual situations. In this regard, the following comment by Jeroen van der Veer of the Royal Dutch Shell group seems appropriate: "The construction of a physical supply chain for hydrogen may develop along lines that we cannot, as yet foresee. A clear path forward will be piggybacking on the existing gas infrastructure. Other paths forward may appear. The important thing here is not to be bound by existing arrangements."[34]

Factors affecting hydrogen infrastructure will include regional dynamics and geographic constraints, distance from production to point of use, and capital utilization. Infrastructure solutions will include: leveraging existing production and delivery infrastructure; point of use generation; combined fuelling and energy; hydrogen feedstock flexibility; and pipeline installation and conversion. The hydrogen supply options include central production and on-site production. Both production options have associated distribution issues and fuel station issues.

[33] T. Gurikova et al, "Transportation Energy Survey Data Book 1.1ORNL for DOE, May 2002.
[34] J. van der Veer, "International Policy Perspectives," 14th World Hydrogen Energy Conference, Montreal, Canada, June 10, 2002.

Presently, about 95% of the 100 billion pounds of hydrogen produced per year is done so as a part of on-going industrial processes. The remaining 5% is a part of the so-called merchant hydrogen market where private companies provide the hydrogen by producing, transporting, and supplying it to end-use customers. This merchant hydrogen market has many years of experience globally on hydrogen production and transport by pipelines. Developments from this substantial existing infrastructure and hydrogen production know-how will be helpful in a variety of areas. Cost-effective hydrogen generators are needed at small sizes and distribution must occur at much lower cost. Standard fueling stations and dispensing systems must be developed, to include solving the mundane aspects of how to fuel individual vehicles using hydrogen pressurized in the 5,000 to 10,000 psi range. Point of use generation of hydrogen will be required. Compact and accurate hydrogen detection sensors are needed. Codes and standards for fueling, distribution, and consumer products must be provided.

Considerable progress has been made in most of these areas during the past several years. For example, for small generators there has been a 30 to 40% reduction in hydrogen cost since 2000. More than 20 companies now offer small generator products. Future cost reductions can be expected and innovation will continue to play a significant role. The ultimate cost will be highly dependent on unit production volume. In the area of fueling, more than 30 fueling station projects are currently underway worldwide. A standard connection system for gaseous dispenser to vehicle is now in use in Europe, North America, and Japan. Vehicles and fueling systems are routinely pressurized to 350 bar (5,000 psi) and 700 bar (10,000 psi) systems are advancing to the testing phase. In the area of storage, active research continues on a variety of new hydrogen carrying materials. Several of these materials potentially meet the DOE capacity target.

Continued progress is being made in areas such as sodium borohydride storage systems and regeneration. In the area of detection, several new sensor technologies beyond that of the ubiquitous straw broom are under development. New products are available with less than 5-second response times and with no response to methane or other flammable gases. The prices range from $500 to $1,000 but are expected to decrease substantially with mass production. To address these and other topics, the DOE has established a Hydrogen Codes and Standards Coordinating Committee the members of which include National Hydrogen Association, International Code Council, National Aeronautics and Space Administration, Society of Automotive Engineers, Natural Gas Vehicle Coalition, Pacific Northwest National Laboratory, and National Renewable Energy Laboratory.[35]

Summary

From these talks and the associated Workshop discussion, it is clear that regional dynamics, distribution distance, and capital utilization will shape the hydrogen infrastructure development. One should expect a heterogeneous infrastructure to result. It appears that significant progress is being made in the key enabling areas. Overall,

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[35] J. Ohi and N. Rossmeissl, "Hydrogen Codes and Standards: An Overview of U.S. DOE Efforts," 14th World Energy Conference, Montreal, Canada, June 9-13, 2002.

considerable hurdles remain before significant progress can be made in the commercially viable hydrogen economy. DOD must remain cognizant of the progress in overcoming these impediments and look for militarily unique opportunities to participate in current and future commercial and government sponsored development of hydrogen. All of the critical path technologies discussed by Lightner (hydrogen production, storage, fuel cell use, and carbon sequestration) may have unique military aspects to explore.

Williams focused on centralized hydrogen production on a large scale and called for testing of various elements in the near term, such as the mega scale demonstration of CO_2 storage in various geological media. An example of such a mega scale aquifer storage project is that at Sleipner Field, in a saline reservoir 800m below the bed of the North Sea[36] where 1M tons of CO_2 are sequestered annually. The Netherlands is sponsoring a project to monitor the Sleipner Field aquifer storage project, starting in 2005[37]; perhaps the U.S. research community could participate in a joint monitoring of this project, possibly under NATO auspices.

Keenan spoke about specialized, smaller scale, unique, customer driven hydrogen production schemes, which also may have DOD-unique potential contributions. An example of the former would be the production of hydrogen on a large scale to serve as a potential feedstock to hydrocarbon production. An example of the latter would be the military's evolving use of very small scale unmanned aerial vehicles (UAVs) and unmanned underwater vehicles (UUVs).

The major DOE work effort in fuel cells described by Surdoval also has potential for unique non-commercial input from DOD whether low temperature or high temperature fuel cells are concerned. Again, as with the production issues, examples of DOD unique energy requirements, weights, and operating environments can be envisioned.

Clearly, the future of hydrogen as a DOD fuel is much further out than any anticipated commercial use. Thus, the primary role of DOD in the emerging efforts to achieve the hydrogen energy carrier commercial economy may involve primarily that of close monitoring its evolution. In the long term, since DOD will be profoundly affected by the development of a hydrogen economy in both its fundamental mission and its daily operations, a further role may be to participate as an active partner in the various unfolding challenges.

[36] www.ieagreen.org.uk/sacshome.htm
[37] http://dbs.cordis.lu/fep-cgi/srchidadb?ACTION=D&SESSION=150722003-8-&DOC=6&TBL=EN_PROJ&RCN=EP_DUR:27&CALLER=MSS_PROJ_FP5_NL_EN

Chapter 4

GAS HYDRATES: ABUNDANT ENERGY FROM THE SEA

Bhakta Rath

Historical Perspective

The discovery that gas hydrates can crystallize as a solid by the combination of water and several types of gases exposed to low temperatures goes back to the 1800s. French researchers in 1888 were the first to report the formation of methane, ethane, and propane hydrates. Results of these studies remained as scientific novelties until the mid 1930s when it was discovered in Germany that gas hydrates forming as solids above 0°C in gas pipelines blocked the flow of natural gas. This observation initiated a flurry of activities both in Europe and in the U.S. to find various inhibitors to prevent hydrate formation in gas transmission lines. During the mid 1960s it was recognized that nature, over millions of years, has deposited vast amounts of methane hydrates along the continental margins in the ocean sediments as well as along the permafrost regions in Alaska, Canada and Russia. These deposits are byproducts of microbial decomposition of organic matter distributed worldwide where the temperature/pressure combination is suitable for hydrate formation. Distribution of organic carbon in the earth's crust as methane hydrates along the oceans and the permafrost regions is estimated to be more than twice that contained in recoverable and non-recoverable fossil fuel (including coal, oil and natural gas). If economically extracted from the ocean sediments, the over 160 m^3 of methane trapped each $1m^3$ of hydrate constitute a large deposit of an alternate energy source. The U.S. Geological Survey estimates the resource potential in the United States to be about 200,000 trillion cubic feet. The current annul consumption of natural gas is about 22 trillion cubic feet. Based on these estimates, at about 1% recovery the deposit has the potential to fill the natural gas needs of the nation, at the present rate of consumption, for the next 100 years. Additionally, for direct fuel combustion methane not only provides high energy density per weight, but also contributes as byproduct minimum $C0_2$ emission; nearly 30 times less than gasoline and 60 times less than coal.

While a great deal of research is underway to understand the nature of hydrate deposits in the oceans and the permafrost regions, the safe and economic extraction of methane from the hydrate fields is not close at hand. Leading efforts are conducted by Japan along the Nankai Trough and by an international consortium along the Canadian artic. The U. S. Geological Survey and the Naval Research Laboratory are engaged at a number of ocean sites along the U. S. continental margins to evaluate the extent of hydrate fields, methane gas cavities and the nature and properties of the sediment.

This chapter provides a synopsis of presentations given by experts in the field of methane hydrates at the National Defense University. The topics and speakers were selected to provide different perspectives on subjects including the current state of our knowledge and technology, industrial viewpoints, international efforts and the law of the sea. The following are reflections of the speakers' viewpoints.

Review of Presentations

William P. Dillon Senior Scientist, U.S. Geological Survey, provided a comprehensive overview on the nature of methane hydrates, their environmental stability, occurrence, and use as a future energy source. It occurs in abundance in marine sediments and stores immense amounts of methane, with major implications for future energy resources and global climate change. Furthermore, gas hydrates control some of the physical properties of sedimentary deposits, and thereby influence seafloor stability.

Its building blocks consist of a gas molecule surrounded by a cage of water molecules. Figure 3 illustrates the structure of a hydrate molecule. Because the material is formed of hydrogen-bonded water molecules, it looks like ice, and is very similar to ice, although of different crystallographic form, having its crystal structure stabilized by the guest gas molecules. The structure of the clathrate cages varies depending on the size of the guest molecule. A unit volume of methane hydrate at one atmosphere (and 0° C) can hold 163 volumes of methane gas at the same conditions.

Many gas hydrates are stable in the deep ocean conditions, but methane hydrate is by far the dominant type, making up >99% of gas hydrates naturally occurring on the ocean floor. The methane is almost entirely derived from microbial methanogenesis, predominantly through the process of carbon dioxide reduction. In some areas, such as the Gulf of Mexico, other thermogenically-formed hydrocarbon gases also create gas hydrates, and other clathrate-forming gases such as hydrogen sulfide and carbon dioxide. Such gases escape from sediments at depth, rise along faults, and form gas hydrates at or just below the seafloor, but on a worldwide basis these are of minor volumetric importance compared to methane hydrate. Methane hydrate exists in several forms in marine sediments. In coarse-grained sediments it often forms as disseminated grains and pore fillings, whereas in finer silt/clay deposits it commonly appears as nodules and veins. Gas hydrate also is observed as surface crusts on the sea floor.

Gas hydrate forms wherever appropriate physical conditions exist, such as moderately low temperature and moderately high pressure. These conditions are found in the deep sea commonly at water depths greater than about 500 m or somewhat shallower depths (about 300 m) in the Arctic, where bottom-water temperature is colder. Gas hydrate also occurs beneath permafrost on land in arctic conditions, but by far most natural gas hydrate is stored in the ocean floor deposits. A simplified phase diagram is shown in Figure 4, in which pressure has been converted to water depth in the ocean (thus pressure increases downward in the diagram). The heavy line is the phase boundary, separating conditions in the temperature/pressure field where methane hydrate is stable to the left of the curve from conditions where it is not. Near the ocean surface, temperatures are too

warm and pressures too low for methane hydrate to be stable. Moving down through the water column, temperature decreases and an inflection in the temperature curve is reached, known as the main thermocline, which separates the warm surface water from the deeper cold waters. At about 500 m, the temperature and phase boundary curves cross; from there downward, temperatures are cold enough and pressures high enough for methane hydrate to be stable in the ocean. This intersection would occur at a shallower depth in colder, arctic waters.

Many estimates of the global amount of gas hydrate have been made. Keith Kvenvolden of the U.S. Geological Survey recently did a survey of these and looked at their variability over time. In 1980 the estimates covered a very broad range, but since 1988 the range of disagreement has been considerably reduced, even though the methods used by ten different sets of workers have varied widely. From 1988 to 1997 the estimates of worldwide methane content of gas hydrate range from 1 to 46 x 10^{15} cubic meters, with a "consensus value" of 21 x 10^{15} cubic meters (740,000 trillion cubic feet—compared to free natural gas (methane) global reserves of ~ 5000 trillion cubic feet).

The organic carbon in gas hydrate is estimated to be twice as much as in all fossil fuels on Earth (including coal). Organic carbon in gas hydrate is also estimated to be about 3,000 times the amount in the atmosphere, and here we are directly comparing methane to methane. As methane is a very powerful greenhouse gas, this reservoir of methane, which might be released to the atmosphere, may have significant implications.

The presence of gas hydrate, identified on the basis of drilling and seismic reflection profiling, has been reported all around the world, but most commonly around the edges of the continents (Figure 5). Methane accumulates in continental margin sediments probably for two reasons: 1. The margins of the oceans are where the flux of organic carbon to the sea floor is greatest because oceanic biological productivity is highest there and organic detritus from the continents also collects to some extent. 2. The continental margins are where sedimentation rates are fastest. The rapid accumulation of sediment serves to cover and seal the organic material before it is oxidized, allowing the microorganisms in the sediments to use it as food and form the methane that becomes incorporated into gas hydrate. In addition to sites in the marine environment, the map also shows some sites where gas hydrate has been reported associated with permafrost in the Arctic, the one location where it has been found in fresh water in Lake Baikal, Siberia and in intermediate salinity (between fresh and oceanic salinities) in the Caspian Sea.

When gas hydrate forms or dissociates within seafloor sediments, this has major effects on sediment strength. Dissociation converts a solid material, which sometimes at high concentrations acts as a cement, to gas and water. Only one triaxial shear strength test of a natural gas hydrate-bearing sediment has been made under in-situ conditions (at the U.S. Geological Survey, Gas Hydrate And Sediment Test Laboratory Instrument—GHASTLI; Booth et al. 1999), confirming the tremendous increase in strength that was expected from gas hydrate in high concentrations. However, in most locations in natural seafloor sediments, hydrate concentrations are fairly low (< 5%), so the cementing effect is minimal. The effect of dissociation of gas hydrate on sediment strength can still be

immense, though, because when hydrate breaks down at shallower depths the products of breakdown, gas and water, occupy greater volume than the gas hydrate they were derived from, and thus the dissociation will increase the internal pressure in the pore space. Such pressures are called "overpressures," pressures greater than the column of water plus sediment above the spot. Generation of overpressures weakens the sediment significantly and is likely to initiate sediment slides and slumps on continental slopes and rises.

The best places to locate gas hydrate deposits for methane extraction are the continental slopes, which seem to have the greatest concentrations of gas hydrate because they contain higher concentrations of organic matter for methane generation by microbes, and have greater rates of sediment accumulation, which buries the organic matter and allows microbial decomposition to form gas. Furthermore, the shallower depths of the upper slopes allow the greatest concentrations of methane compared to conventional gas traps.

From the minimum depth of hydrate stability down to total depths of about 1600 m, gas is held in hydrate in concentrations greater than in conventional traps. However, the maximum concentration of methane in hydrate is essentially fixed, in contrast to free gas in reservoirs, where pressure increase will cause increased concentration, so at greater depths, free gas reservoirs will be more concentrated as a result of the higher pressure. The fixed concentration of gas in gas hydrate also means that shallower gas-hydrate deposits will release gas that will expand more and fill a greater proportion of the pore volume than comparable deposits at greater depths (at greater pressures). For example, a 5% pore concentration of gas hydrate at 1000 m will provide the same gas expansion as a 15% concentration at 3000 m. Therefore, there is greater likelihood at shallow depths of exceeding the minimum limit of gas volume needed to generate spontaneous gas flow.

Both the concentration factor at shallow depths and the expansion considerations suggest that the shallower part of the gas hydrate range may be more favorable for gas extraction—perhaps in the 1000-2000 m range of water depths. Methane probably will be extracted from hydrate by using a combination of depressurization (perhaps primarily), warming (perhaps using warm fluids from deeper in the sediments), and selective use of chemical inhibitors to initiate dissociation at critical locations.

The future of gas hydrates as an energy resource depends on the evolution of: 1. Geological studies (to identify concentration sites and settings where methane can be effectively extracted from gas hydrate); 2. Engineering (to determine the most efficient means of dissociating gas hydrate in place and extracting the gas safely); 3. Economics (the costs are likely to be higher than for extraction of gas from conventional reservoirs); and 4. Politics (increased energy security and independence for energy-poor nations are significant driving forces). Table 6 gives the global organic carbon distribution.

TABLE 6.
Global Organic Carbon Distribution in Gigatons (Gt = 10^{15} g) (Kvenvolden, 1988)

Gas Hydrate		Land	
(methane)	10,000Gt	- biota	830 Gt
		- detritus	60
Fossil Fuels	5,000	- soil 1400	
		- peat500	
Atmosphere			
(methane)	3.6	Ocean	
		- marine biota	3
Dispersed Carbon	20,000,000	- dissolved	980

Arthur H. Johnson, Chair, Advisory Board on Methane Hydrates for the Department of Energy, pointed out the great diversity of industry viewpoints, which include issues on exploration and use of methane hydrates as a future source of energy. Most energy companies have become progressively more short-term focused, as evidenced in the declining corporate support on energy research during the last decade. Any investment in research is either driven by expectations of short-term returns or prevention of losses. Investments made by Anadarko and British Petroleum on the North Slope of Alaska in pursuit of hydrate finds resulted from the successful project at the Mallik well in Canada and the current status of the U.S. market for natural gas. There was the so-called "gas bubble" during the decade between 1985 and 1995 when an excess of natural gas on the market kept the price at $1.60 per thousand cubic feet (10^6 BTU), which rapidly changed during 1996 to 1999 to $2.35, continuing to increase during 2000 to the present to an average price of $3.72 at the time of this workshop. At these prices, gas from hydrates of the Alaskan and the Canadian Arctic shipped through pipelines could compete in the U.S. and Canadian market.

The global view of the future energy resource and demand, as shown in Figure 6, reveals that for oil consumption, the per capita income of nations is a linear function of oil consumption. As the nations strive for improved standard of living the energy usage will increase significantly with an increasing competition for world's energy resource.

Transportation of energy is yet another issue while oil can be shipped by tankers and maintain a global price, natural gas prices vary depending on shipment via pipeline or as LNG (shipped as a liquid at -260°F). In Japan for instance the gas price has gone up between $15 to 30 per thousand cubic feet (10^6 BTU).

The U.S. industry foresees significant shortfalls in gas due to the declining production from existing fields and about a two-year life of new fields. While demand continues to increase, domestic fields' productions continue to diminish. Some of the possible solutions are: (1) open additional areas, however controversial for exploration and production, (2) develop unconventional gas resources, such as coal bed methane, deep

gas, shale gas, and gas hydrates, and (3) import more LNG paying a higher price, which may be further aggravated due to issues on energy security, since the major areas of supply are middle east, the former Soviet Union, Indonesia and West Africa. Global distribution of gas reserves is shown in figure 7.

Industry's view on gas hydrates is one of curiosity, with the possible exception of the Gulf of Mexico where safety issues near the platforms is a matter of concern. Gas hydrate development is considered as: (1) not a near-term return on capital, (2) not a part of company's core business, and (3) not technologically feasible due to unresolved issues on the sediment structure, deep water drilling and state imposed drilling bans. Hydrate deposits in Alaska are near surface and can be produced sooner, but gas extraction from hydrates in the Gulf is somewhat in the distant future.

The known facts on gas hydrates are: (1) widely spread along continental margins and the artic regions, (2) while the shales have low hydrate concentration, the sandstones, particularly those in the deeper strata of ocean sediments contain a high concentration of hydrates. In the U.S., Blake Ridge off the Atlantic Coast, Cascadia Margin off the Pacific Coast, North Slope of Alaska and the Gulf of Mexico are reported to have high deposits. From an industry standpoint the major points are: (1) what is the ultimate gas recovery from a given source, (2) what will be the rate of production from a hydrate well, (3) what is the operating expense, and (4) what would be the cost in comparison to other gas sources including imported LNG. Federal actions which could promote commercialization of gas from hydrate wells are: (1) enhanced research funding, (2) easing royalty on gas production from offshore and the Artic and, (3) providing a long-term continuity of Federal commitment to keep industry involved. In summery, the development of unconventional resources, such as gas hydrates, to supplement LNG imports is essential since the conventional domestic gas production will not be able to meet demand in the near future.

Timothy Collett, research geologist of USGS, served as project chief of the North Slope of Alaska Gas Hydrate Project and recently completed an international collaboration effort on gas hydrate research at the Mackenzie Delta in the Beaufort Sea area of Canada. The nations participating in this joint venture included Canada, Japan, Germany, India, and the United States. Dr. Collett provided an overview on how, why, and where hydrates occur along the continental margins and in the permafrost regions of the Arctic, followed by an account of the current status of research and discoveries by various nations.

The amount of gas within hydrates has been estimated by a number of investigators since 1981. In-place natural gas resources in terrestrial gas hydrates are estimated to be somewhere between 1.4×10^{13} to 3.4×10^{16} cubic meters, whereas the natural gas resources in oceanic gas hydrates are between 3.1×10^{15} and 7.6×10^{18} cubic meters. National and regional estimates of the amount of gas as hydrates, which have been reported from various measurements, are presented in Table 7.

Table 7. National and regional estimates of the amount of gas as hydrates that have been reported from various measurements

Location	10^{12} cubic meters	10^{12} cubic feet	Reference
United States	8997	317684	Collett, 1995
India	122	4308	ONGC, 1997
Blake Ridge, USA	18	636	Dillon and others, 1993
Blake Ridge, USA	70	2472	Dickens and others, 1997*
Blake Ridge, USA	80	2825	Holbrook and others, 1996*
Blake Ridge, USA	57	2013	Collett, 2000*
Blake Ridge, USA	38	1342	Collet, 2000
Nankai Trough, Japan	50	1766	MITI/JNOC, 1998
Andaman Sea, India	122	4308	ONGC, 1997
North Slope, Alaska	17	600	Collett, 1997

*Includes associated free gas

Perhaps the most extensive studies on hydrate deposits to date, conducted by USGS and the Naval Research Laboratory, have been in the Blake Ridge region off the coast of the Carolinas where there are indications of significant deposits with an average estimate of about 2000 trillion cubic feet (compared to world total natural gas reserves estimated at 5000 trillion cubic feet). Hydrate reservoirs in the Blake Ridge region at four different sites and the estimates of the depth of gas hydrates and the volume of gas per square kilometer are provide in Table 8.

Table 8. Hydrate reservoirs in the Blake Ridge region at four different sites and the estimates of the depth of gas hydrates and the volume of gas per square kilometer

Site/Well	Depth of gas hydrate (m)	Thickness of hydrate (m)	Porosity (%)	Hydrate saturation (%)	Volume of gas per square km (cubic m)
ODP Site 994	212.0-428.8	216.8	57.0	3.3	669,970,673
ODP Site 995	193.0-450.0	257.0	58.0	5.2	1,267,941,673
ODP Site 997	186.4-450.9	264.5	58.1	5.8	1,449,746,073
ODP Site 889	127.6-228.4	100.8	51.8	5.4	466,635,705

A second comprehensive study along the Prudhoe Bay Alaska, cirque-tarn and Mackenzie Delta, Canada, conducted between 1993 and 1999, indicated deposits of 42×10^{12}, 60×10^{12} and 6.6×10^{12} cubic feet, respectively. Extensive research is needed to identify the amount and exact locations of hydrate fields and the sediment characteristics before appropriate production methods can be designed for their economic use. Three production methods are proposed, identified as depressurization, thermal injection, and inhibitor injection methods. Figure 8 provides a schematic illustration of these approaches for gas extraction.

International programs on gas hydrate research are conducted by individual nations under different project titles. Canada conducts its efforts under “New Canadian Gas Hydrate Research Program” supported by the Geological Survey of Canada. The Canadian gas hydrate program focused on the marine region around Vancouver Island and artic region around the Mackenzie Delta. Plans are to emphasize studies on environmentally friendly sorts of energy benefits of hydrate production to the northern and coastal communities, assessment of geologic hazards and climate change. Laboratory studies to develop exploration models, quantify physical properties of hydrates and develop economically viable production methods are underway. In the United States the major effort on “Methane Hydrate Research And Development” is managed by the U.S. Department of Energy with support from the Naval Research Laboratory, National Science Foundation, USGS and the Department of the Interior.

In Japan, the “National R&D Program for Methane /Hydrate Resources” is sponsored by the Ministry of International Trade and Industry (MITI) and the Japan National Oil Corporation (JNOC). Japan launched its program in 2001 for a 5-year study of methane hydrate deposits at the Nankai Trough and Okhotsk Sea. Additionally, it has also embarked on a comprehensive plan to be conducted over a period of 16 years in three phases focused on research areas related to exploration, modeling, field testing, development technology and health-safety-environmental assistance. Japan’s investment is perhaps the largest of its kind in this field of research.

India has initiated its National Gas Hydrate Program (NGHP) under the Ministry of Petroleum and Natural Gas in 1997. This program was reconstituted in 2000 with the direction of the Directorate General of Hydrocarbons (DGH). Efforts addressing issues on drilling, production, geoscience, and environment are under the auspices of Office of Natural Gas Corporation (ONGC) and transportation under the guidance of Gas Authority of India Limited (GAIL). India has completed a preliminary survey of the prospective regions with high gas hydrate concentrations beyond the 700 m water depth using geologic and thermodynamic data and expects to complete its resource estimates by the end of 2003 and initiate assessment of realities through various laboratory studies, deep water coring and drilling operations development of gas hydrate production pilot and economic studies.

Dr. Collet concluded his remarks on the importance of extensive research and development on the subject before economically producing methane gas from hydrates in deep water sediments. In addition to a need for significant improvements in geophysical tools, improved understanding of rock properties is needed for better modeling of the hydrate reservoir. Several technical areas should be addressed in a concurrent manner with improved international collaborations along with social and regulatory pressures leading to economically producing methane from deep-water deposits.

Brad Tomer, Program Manager, DOE, provided a historic perspective of methane hydrate research conducted by the Department of Energy and the current responsibility and execution plan of DOE in response to Congressional authorization for methane

hydrate research. Following the discovery of massive hydrate deposits off the coast of Guatemala in 1982, DOE, in collaboration with other organizations, embarked on a ten-year program to establish a foundation on methane hydrate science. This study reviewed the widespread natural occurrence of hydrates in the deep oceans and the artic regions. During the early 90s it was recognized that more of the organic carbon is stored within hydrates than is present in all the worlds coal, oil and non-hydrate natural gas combined. Concerns were raised on the linkage of hydrate deposits to catastrophic instability of continental shelves and to the lack of understanding of the global carbon cycle. These preliminary findings also raised the question on the role of periodic and massive dissociation of methane from hydrates over geologic time in affecting the earth's climate. Finally, the question was raised as to whether the abundance of this new resource could meet future energy needs.

Since 1999 the Department of Energy has designated the National Energy Technology Laboratory to develop a comprehensive R&D plan in collaboration with MMS, NOAA, NRL, NSF and USGS. A joint effort with a total investment of approximately $15M in FY03 is underway to address various issues relating to detection of hydrate fields, sediment stability, carbon cycle, global climate, deep-sea life, and safety. An interagency coordinating and planning committee and an industry/academic advisory panel, both chaired by the Assistant Secretary of Energy, conducts plans for research investment. The program organization structure is presented in Figure 9.

A make up of the program plan was formulated from two workshops conducted by DOE in 1998 and 2000. The technology road map from characterization to production conducted over a 13-year period is illustrated in figure 10. The program envisions providing guidelines on the safety of deep water gas recovery and sea floor stability by 2008 and to understand the impact on global climate by 2010. It is anticipated that the necessary knowledge base for commercial production with minimal impact on the environment and the technology suitable for economically extracting methane will be available by the year 2015.

The efforts are directed on two fronts, 1) laboratory studies of synthetic hydrates, hydrates/sediment mixtures and simulation of sea floor processes with a concurrent program and 2) studies of hydrates in their natural settings through development of improved geophysical tools (led by researchers at the Naval Research Laboratory (NRL)) to remotely determine the occurrence and the characteristics of hydrates deposits and to develop remote sampling and analytical tools to collect real world samples for evaluation either in the field or through successful transport to the laboratory. The areas identified for field studies are the coastal regions of the Pacific and Atlantic, the Gulf of Mexico and the artic regions in Canada and Alaska. The Gulf of Mexico has been a focal point for extensive studies in partnership with industries such as Chevron Texaco, Schlumberger, Conoco Phillips and Halliburton. USGS, CMRET and NRL are principal participants in this study. The other focal point in the artic fields in collaboration with international partnership has been directed to drilling and tests at the Mallik well in the Mackenzie Delta of Canada.

Tomer concluded with high expectations of future energy derived from gas hydrate deposits. The worldwide distribution of this energy resource has the potential for changing the balance of power. However, significant R&D is needed before exploitation of this resource. If funding level supports the planned road map, methane from hydrates could contribute to the American natural gas supply by 2015.

Dr. Emrys Jones of Chevron Texaco, manager of the Joint Industry Project, actively involved in the evaluation and development of technologies for the extraction of gas hydrates in the Gulf of Mexico. Seven oil companies, along with MMS and DOE, are co-participants and sponsors of these projects. Dr. Jones presented the industry's overall view. At the current state of the art of infrastructure and drilling technologies, with known flow rates from hydrate wells, investing in a stand-alone hydrate extraction scheme is uneconomical at the current U.S. natural gas prices. Stand-alone offshore development can cost billions of dollars and requires that the uncertainties be as low as possible.

Of course, long-term trends could affect the supply and demand balance. It is quite clear that the United States will have to import a large part of its natural gas early in the 21st century. Figure 11 shows the years of supply of natural gas in different regions of the world at the 1996 consumption levels. Historical variations in production, consumption and price of natural gas since 1949 are illustrated in Figure 12. The price escalation is expected to continue as we become increasingly dependent on LNG imports.

Two main factors that could alter the supply and demand picture are the consumers increasing interest in energy that is cleaner and easier to use and development of new technology to provide more economic industrial application. Some of these factors have clearly influenced the replacement of coal by natural gas for residential and commercial use. A similar shift from coal to oil as the primary railroad transportation fuel was seen in a period of less than 15 years. If, in fact, the automobile manufacturers successfully develop fuel cells for transportation, gas could replace oil as the primary auto transportation fuel in 10-20 years. Acceleration of this transition could happen if the green movement continues and the developed countries commit to reduce their carbon output.

Petroleum companies typically invest on an expected value basis, which is dictated by risk weighted net present value. The expected value is the difference between revenue and cost; the revenue projection is evaluated on the basis of estimated deposits (i.e. how much is there), rate of production and the market price. The cost includes expenditures for exploration, drilling and completion, facilities and transportation. These elements dictate petroleum company's investment plans.

In order for gas hydrates to be a viable commodity for industrial interests, there has to be: 1) significant improvement in geophysical tools to enhance confidence in the presence and the quantity of hydrates in the ocean sediments, 2) high confidence in the mechanical properties of the sediment for safety and facility design, 3) improved reservoir modeling

to evaluate the flow rate using different production systems and 4) low cost for safe drilling and extraction.

Mr. Jones concluded his remarks by recognizing that gas hydrates are a huge untapped U.S. and global energy resource. Advances in several technical areas in research and development are required before gas hydrates can be exploited economically. Social pressures and technology advancements would have a significant impact on the exploitation of gas hydrates in the near future.

Dr. V. Kamath, Senior Research Engineer, Reliance Industries Ltd., India, provided a comprehensive review of the current status on methane hydrate exploration along the continental margins of the eastern coast in India. Topics discussed included the natural gas supply and demands in India, exploration of hydrates in deeper waters and industry experiences on drilling for hydrates including issues related to mitigation of hydrate melting during drilling and production. The gap between gas supply and demand in India is widening at an alarming rate. The demand is expected to more than double during the coming decade. Figure 13 provides a supply/demand comparison between 1995 and 2020. The nation has divided its deepwater offshore zones into 50 blocks, 32 of which have been given to a vertically integrated company called Reliance Industries, Ltd. (RIL).

The RIL has initiated explorations on two of its assigned blocks along the eastern offshore of the Bay of Bengal, known as the Krishna-Godavari basin and the Mahandi basin. The 2D seismic evaluations of well-drilled samples indicate vast reserves of methane hydrates and gas cavities below the BSRs. Reliance estimates a total reserve of about 1900 trillion cubic meters (TCM) (670,000 trillion cubic feet) of gas in its offshore regions. The country's conventional gas resource is about I TCM. Table 9 provides India's estimates of gas hydrate reserves along its EEZ. It is estimated that even at a 1% recovery of India's hydrate deposits in deeper waters, it will provide the nation's gas demands for the next 150 years. Reliance has an ambitious plan to direct $1.5 billion over the next two years to develop gas fields. Results of studies conducted thus far along the Krishna-Godavari basin suggests a discovery of 15 TCM, at a distance of 40 km from the shore, at water depths ranging between 400 and 2700 meters. These figures are extracted from 8 wells drilled in water depths ranging 642 meters to 1756 meters at a seabed temperature of 3.2°C. A parallel effort is also directed in the extraction of coal-bed methane.

Table 9. Estimated Gas Hydrate Reserves of India

	Probability of equal to or greater than				
Plays	95	75	50	25	5
Bombay Offshore	135	307	454	630	852
Kerala-Konkan Offshore	62	221	1137	1566	2299
Northern Arabian Sea	226	440	595	798	1092
Southern Arabian Sea	0	0	312	709	1094
Eastern Offshore	1038	1527	2168	3181	4525
Northern Bay of Bengal	245	334	468	648	937
Southern Bay of Bengal	188	367	1022	2468	3773
Total Reserves (TCM)	1894	3196	6156	10000	14572

Source: National Gas Hydrate Program INDIA

Additionally, RIL has conducted studies on the potential melting of the hydrate zone around the well bore during long-term production of gas from the sea floor. The impact of extraction of gas from deeper sources, where the temperature of the gas could be as high as 50 to 70°C higher than the upper hydrate zone, which contributes to melting and destabilization of the sediment, is under study.

The results of this simulation and modeling on heat transfer to the sediment through conduction, convection, radiation and Joule Thomson expansion are essential to the predication of sediment behavior during long-term production process.

Dr. John Rees, senior staff of British Geological Survey, stated that the overriding perspective on gas hydrates in Europe was from the standpoint of geological hazards and the associated climate changes. There is essentially no research focus on hydrates as an energy resource. 11 European nations are currently funding gas hydrate research with Germany the principal player. Extensive surveying of hydrates has taken place in the Arctic, all around Scandinavia, the Black Sea, the eastern Mediterranean and Gulf of Cadiz.

Interest and work in Europe is just beginning in characterizing hydrates in local environments. This is a precursor to understanding the thermodynamics and mechanics of hydrate changes within the various structures. There is currently a preliminary interest in recovering hydrates and evaluating their composition and structure.

In order to study hydrates systematically in the laboratory, some work has been done on synthesizing carbon dioxide and tetrahydrofuran hydrates in addition to methane

hydrates. It is much easier to study the stabilization and destabilization phenomena of gas hydrates using carbon dioxide hydrates.

The outlook for future funding for additional hydrate work in Europe look very bleak at the moment. Individual countries such as Germany and UK are well intentioned to continue hydrate studies but primarily focused on hazards and not resources. The European hydrate coring programs are well developed. The near future focus of research is towards greater analysis of physical properties of hydrates. Rees closed by indicating that progress might be achieved in hydrate research by more international collaboration.

John Moore, Director for the Center of Ocean Laws and Policies, University of Virginia and chair of the National Security Council task force on the law of the sea, provided a detailed description of the articles of the 1982 United Nations convention on the ”Law Of The Sea”, as they pertain to the exploration and exploitation of methane hydrates as well as other activities related to ocean thermal energy conversion and ocean wave energy extraction. The articles of the convention have been adopted by 140 nations. The U.S. Government, while not formally adhering to the guidelines of the treaty, has regarded the treaty as a customary international law. It is expected that, in the near future, the U.S. Senate will provide advice and consent for joining the 1982 Law Of The Sea Convention. When the convention is adopted by the U.S. Government, it will formally be a signatory to the treaty.

When one operates in the territorial seas of a nation, it is evident that one has to abide by the imposed restrictions of that nation including the international restrictions applicable for such operations. Additionally, Article 2 of the UN convention describes the sovereignty of the coastal states beyond their land territory that has the control of the territorial sea. The maximum breadth of the territorial sea is 12 nautical miles. This law is modified on the basis of the proximity of other nations. The Greek government, for example, because of the problems related to the Greek-Turkey dispute, has not extended its territorial jurisdiction beyond 6 nautical miles off its territorial sea.

Article 56 describes the controls of the coastal states in what is known as exclusive economic zones (EEZ). It states that in the EEZ the coastal states have the sovereign rights for the purpose of exploring and exploiting the natural resources, whether living or non-living, in the waters including the seabed and subsoil. The maximum breadth of the EEZ is 200 nautical miles. This is an area of high seas freedom that is important for not only the exploration of resources, but also for navigational purposes. Article 77 of the Law of the Sea Convention provides a description of the continental shelf and the right of the coastal states on activities related to the seafloor, seabed and subsoil. It clearly provides guidelines for anyone wishing to undertake activities with the expressed consent of the coastal states. In situations where the continental shelf extends beyond the EEZ, the extended areas again fall under the jurisdiction and the sovereign rights of the coastal states and all other nations for the purpose of any exploration or exploitation. Figure 14 shows a global view of the continental margins beyond the 200 nautical miles from the baseline. Figure 15 provides a graphic description of the continental shelf, EEZ, and the territorial sea. Article 87 on the freedom of the high seas provides description of the

jurisdictional authorities open to all states on the high seas, whether coastal or landlocked. For example, if the U.S. Navy is interested in ocean thermal energy conversion systems (OTEC facilities) beyond a 200-mile economic zone, it can operate under high seas freedom. The high seas freedom would be particularly applicable for floating OTEC facilities not related to the sea floor or the continental shelf.

Regarding exploration and extraction of methane from the seabed hydrates, Article 76 and Article 208 describe environmental requirements in the Law Of The Sea Treaty. The coastal states have the authority to enforce environmental requirements for such explorations. The articles also anticipate that, at some point, there will be an international negotiation for a new convention to set minimum international standards for environmental protection on continental shelves that will apply to extraction of all energy resources from the seabed. Article 246 provides guidance on marine scientific research activities as opposed to exploration and exploitation. The coastal states may, at their discretion, withhold their consent to conduct marine scientific research either in the EEZ or on the continental shelf if such research efforts have direct significance for exploration and exploitation of natural resources, whether living or non-living.

Yet on another topic, Prof. Moore provided the existing jurisdictions based on the U.S. national law, which divides the authority of the federal government and the coastal state in the offshore areas. To clarify the territorial authority of the U.S. federal government and the individual states, the U.S. Supreme Court provided the political compromise referred to as Outer Continental Shelf Act which gave the coastal states the territorial authority of 3 nautical miles with the exception of the Gulf states which have the jurisdiction of 9 nautical miles, beyond which it is completely federal. The laws governing the incentive structure for the coastal states described in part by the coastal zone management act and a variety of others provide a complex set of guidelines. These sets of laws need a revision identifying the percentage of revenue on offshore activities on oil and gas. Prof. Moore concluded his overview with the statement that the laws of the sea although generally accepted by all nations and states, within U.S. federal jurisdiction, need considerable revision and clarification to provide a coherent set of guidelines for operations research, exploration and exploitation in the oceans.

Summary

In summary, the general view is that methane hydrate deposits in the continental margins and in the permafrost regions of the world hold high potential as an alternate energy source for domestic and industrial use. Extensive research investments in development of advanced tools to identify the presence and quantity of hydrates, physical properties of the sediments of the hydrate fields, improved predictive models to evaluate flow rates and the economics of production and on issues related to safe drilling and extraction is needed. While most of ground transportation fuel needs could be met by the development of fuel cell technologies, DOD requirements for fuel, primarily for aviation, require conversion of methane to liquid hydrocarbons. To meet its future needs, DOD should develop a comprehensive R&D investment strategy to exploit methane hydrate as a source of energy.

Chapter 5

RENEWABLE ENERGY FROM THE OCEAN

Dennis Hardy

Introduction: Because of the potential for unique military uses, the organizers included a very short workshop session covering the current state of the art of one of the largest untapped energy sources, sea solar power. Gas hydrates represent vast potential non-renewable energy sources from the ocean. But even that source of power is only a fraction of the energy that is theoretically available for recovery from the oceans from the renewable sources of tides, waves, wind and thermal energy, provided that energy recovery rates and energy storage is possible.

As discussed by Taylor below, the actual total recoverable energy from tidal sources is severely limited by the very few sites available worldwide and by the very high capital costs of installation. Off shore wind will not be developed until on shore sites have been developed, again due to the much higher cost of installation and maintenance off shore. Thus these two areas of ocean energy were not addressed in the workshops.

Ocean thermal energy could be recovered by a heat engine and was actually proposed as early as 1881 by J. D'Arsonval. Early attempts to actually construct such devices by Campbell in America and by Dornig and Boggia in Italy were unsuccessful. In 1926 G. Claude made another unsuccessful attempt in the Caribbean. Following this, J. Anderson in 1964 analyzed Claude's efforts from 40 years earlier and concluded that the main problem was design deficiencies. Anderson proposed many new designs from 1966 to the present time and Nicholson below discusses his current designs are in detail. To appreciate the vast amount of thermal energy from the oceans one can estimate that every day the ocean absorbs enough heat from the sun to equal the energy contained in 250 billion barrels of oil (8 times the current world consumption of oil annually).

This same vast level of energy can be estimated from waves. In some favorable locations one can estimate that waves are capable of producing 65 MWatt-hours per mile of coastline. One tenth of a percent of the energy in ocean waves would be capable of supplying the entire world's energy requirements five-fold.

These two sources of renewable ocean energy, essentially untapped to date, are really only capable of providing electricity. True, this electricity is not generated from any fossil fuels and thus is carbon dioxide free, and true, this independence from fossil fuels means that there are no geo political energy source problems or constraints, and true, the

economics appears favorable at the present time, but how is the military to make any use of this resource in its war fighting operations?

Although the presenters below were not asked this question specifically, it is relatively straightforward to envision that from this ocean based electricity it is only an additional step to produce hydrogen from water. But as we see from the workshop proceedings and other recent DOD studies, hydrogen, even extremely cheap hydrogen, cannot function militarily now or in the future. If a source of carbon such as ocean-dissolved carbon dioxide could be recovered economically near the wave power generators or the ocean thermal power generators, then the possibility exists for synthesizing liquid hydrocarbon fuels. This would present a seamless and transparent hydrogen carrier to all current and future military power generators and engines. Thus in future studies, these two power sources must be considered as part of a larger hybrid system for transforming electrical energy from the ocean into liquid fuels for military use.

Review of Presentations

Dr. George Taylor (President of Ocean Power Technology Corporation) discussed the use of tides and waves as renewable sources of energy. First, he described the use of tidal energy, which requires special location in regions of high tides in order to efficiently produce energy. There have been two commercial systems built to date. One is a large French system in Brittany build in the 1960's that generates 240 megawatts of peak power and 540 gigawatt hours per year. More French systems are not planned due to high capital costs of construction. The second small system is in the Bay of Fundy between Canada and the United States and it is a 20 megawatt system.

The main disadvantage of tidal power is that it is limited to about 40 sites worldwide and that it is very high cost to construct such systems. Wave energy systems can be used almost anywhere in the world and are normally located near centers of high population. 70% of the world's populations live within 50 miles of the coastline of the oceans. Wave power is available about 90% of the time as opposed to solar availability of 20% and wind availability of 35%. Wave power is environmentally very benign, non-polluting, generates no noise, and if located offshore is not even visible. The energy is relatively concentrated. As an example, the energy in 100 square miles of surface area off the coast of California could provide all the electrical power of California.

The best wave energy resources are above the Tropic of Cancer and below the Tropic of Capricorn (away from the equatorial regions). The total energy from waves in these regions is about twice the world's current electricity production.

There are two possible wave energy systems—offshore and onshore. The number of sites around the world for offshore systems is essentially unlimited, but onshore sites are quite limited. The offshore system construction cost is about $900 per kW to build a 100 megawatt size power station. Taylor's company's first commercial system is being built in Hawaii and will be 50 kilowatt total. A second system there will be built next year and be 125 kilowatts. These small systems only occupy a relatively small area. A 250-

megawatt plant would be about 100 acres. The cost to build is comparable to that of building a large-scale wind facility built onshore. Because of environmental concerns in Europe some large wind facilities will now be built offshore at a cost of about 80% higher than onshore. Finally, the cost of electricity would be about 3 to 4 cents per kilowatt for large wave systems.

The Marine Corps is also planning to build a one-megawatt facility in Hawaii using offshore wave technology. The additional problem of barnacle cleaning appears to have been solved by standard 3-year procedures that involve removing the wave generator buoy from the water.

Robert Nicholson (President of Sea Solar Power International, Inc.) began by reporting that his company was currently building the first 10-megawatt Ocean Thermal Energy Conversion (OTEC) land based power plant. He feels, however, that this technology represents a tremendous ship building opportunity in the United States if sea based plants can be constructed in the near future. The OTEC technology appears to address many issues such as global warming, energy supply, water shortages and environmental problems.

His approach in designing current OTEC plants uses refrigeration principles and not land based power plant design principles. The technology recognizes that the ocean is the largest solar collector in the world and already contains 300 times the amount of energy that is consumed daily worldwide. It essentially provides a constantly available base load power that is renewable and low cost. He states that a hydroelectric power plant costs about $3,500 per kW to build and is available about 55% of the time. In comparison a floating OTEC plant estimate to build is about $2,500 per kW (for a 100 megawatt plant) and it will be available about 90% of the time. In addition a 100 megawatt floating plant ship would produce about 32 million gallons of fresh water per day and about 100 million dollars of aquaculture products per year. The smaller land based 10 megawatt plant would produce 3 million gallons of water per day and 10 to 30 million dollars of aquaculture per year.

The current design differs significantly from previous DOE designs of the 1970's and 1980's. A floating 100 megawatt plant would have a cold water pipe about 3000 feet long. The ship would be about 750 feet long, 150 feet wide and 80 feet high and would weigh about 25,000 tons and be designed to operate about 20 to 30 years at sea.

During the new design it was determined that it was economically impossible to build an efficient OTEC plant with standard off the shelf components. The demands of a low temperature cycle OTEC plant were best met with refrigeration principles and not power plant principles. This means that it is not desirable to construct a single 100 megawatt turbine but 4 separate turbines in order to gain efficiency and economic operation. Also unique in the new design is the choice of a non-corrosive working fluid. Taken as a whole the new design is about one-eighth the size and weight of the former DOE designs and also quite a bit more efficient than earlier DOE sponsored commercial designs.

This technology represents a vast untapped source of renewable energy from the sea that should be considered as part of a future DOD energy portfolio.

Summary

Wave power generation development is slightly ahead of ocean thermal power generation at the present time. This is primarily because the scaling factors vs. cost of construction favor wave power. Clearly both of these power sources warrant a detailed military study for the generation of future energy and fuels. At the moment, both of these systems' capital costs to install are somewhat lower than off shore wind installation. Military interest in on shore wind generation is somewhat limited due to the unlikely development of carbon dioxide recovery from the atmosphere as a feedstock to produce liquid hydrocarbons.

A preliminary examination of the theoretical energy yield from these systems appears very favorable. In addition both of these renewable energy sources pose minimal problems from an environmental standpoint. Indeed, it is surprising that the current energy giants are not more heavily developing wave power generation commercially since transmission of the electricity to land would immediately begin to obviate the current energy deficit of the United States.

Finally, is must be asked in what time frame should these renewable ocean resources be explored for potential military applications? It is instructive to note that both of these energy sources were highly recommended to be studied immediately (along with a number of other energy sources) in a 1974 report from Naval Research Laboratory. This report was a study in response to the national energy problems of the early 1970's and was from the point of view of NRL involvement in the Navy's energy research needs only. That report did not prioritize the relative potential importance of the recommended studies and as the political nature of the crisis became apparent many of the studies were abandoned or never started. Ocean renewable energy sources fell in that last category.

As the real crisis of the end of cheap energy sources from fossil fuels approaches, ocean renewable energy sources will again appear on lists of potential military solutions to rising costs and decreasing availability of fossil fuels. Unlike the 1970's when the crisis was perceived to be upon us *now*, the real crisis of cheap fossil fuel decline is correctly perceived to be some time in the future. The magnitude of this future crisis is easily predicted—it is immense. Since we appear to be given a few more years to prepare for it, and the development of renewable ocean energy sources will require several years for wave energy and several decades for thermal energy, it is hoped that the studies recommended as a result of these workshops will place not only high priority but immediate action on these long neglected topics.

Chapter 6

ENERGY OVERVIEW

Dennis Hardy

Each of the workshop sessions was focused on a particular topic or theme and those particular topics were then assembled in the various chapters of this book. The final session, however, was devoted to a more generalist overview approach. The 4 speakers were asked to try to summarize the entire workshop by trying to provide a bigger picture and a context for the previous sessions.

First there was a discussion of the recent government wide energy policy paper in Great Britain, which is described below in some detail. One important feature of this address was that it covered an entire nation's future energy policy and was portrayed as a sort of potential model for the rest of the world.

The following speaker treated the entire world and the United States as models for energy supply and demand in a strikingly simplified way that was used to place into context many of the particular topics covered throughout the workshop. Indeed, this model was able to essentially examine all the possible future energy scenarios.

In order to put the entire U.S. DOD energy picture into context, the next speaker described the current situation, which is a "business as usual" approach. This is geared to a worldwide energy supply system that supplies at the lowest possible price yet still meeting the diverse and difficult war fighting requirements of the modern military.

Finally, a broad assessment of the world's current and near future energy balance which by necessity must be dominated by the oil and gas industry was given in a no-nonsense investment banking point of view. To be able to grasp the current world energy situation is difficult and a massive undertaking. To be able to try to predict energy futures is an even more difficult and almost overwhelming undertaking. This difficulty caused by immense complexity of the world situation in energy simply adds to the cloudiness of the prognosticator's crystal ball.

The details of the summary session speakers' remarks are given below. Common threads do appear in the rich tapestry woven by them. One of these threads is the sheer immensity of energy needs on national and global bases. Another is that however immense the needs are now, the future needs will be even greater. A third thread is that the infrastructure of today did not appear overnight but took not only many decades but many trillions of dollars worth of investment. A fourth thread was that all the non-renewable fossil fuel sources provided immensely cheap sources of energy ranging from only a few dollars per

million BTUs to as much as $15 per million BTUs. This could be compared to the price of individual human energy output of millions of dollars per million BTUs available for almost all of recorded history. A final thread was that not only were the currently used sources of energy very cheap but they are generally easy to manipulate, store and use with liquid fuels being easiest, followed by gases followed by solid sources.

Review of Presentations

John Hassard (Imperial College, London) gave a detailed and lively review of the recently released UK white paper on energy for that nation. He began by identifying the major driver of the white paper, which originated in a UK Green Party interest in the government's ratification of the Kyoto Protocol and the immense impact of this on carbon emissions. In addition to this there were various other political drivers of the white paper including the ensuring of heating of homes for fixed income retirees.

He indicated that the paper called for a diverse energy mix and this appeared sensible since diversity enhanced both supply and also management of demand. The increased demand for electrical energy to power home and office air conditioning as global "warming" increased in northern latitudes would also impact a need to increase energy efficiency in these items.

He mentioned that the energy minister was actually very much in favor of nuclear power but that the white paper seemed to essentially kill this potential future power source by putting off a decision to build or re-build nuclear power plants.

The report appears to paint a bright future picture with challenges that can eventually be dealt with, but however, falls far short of mentioning the potential for a "perfect" storm which is approaching. He sees Britain as a laboratory for the rest of the world and one that will experience indicators of future energy problems before the rest of the world sees them. One of these indicators is the possibility of power shortages. He indicates that use of gas and oil is increasing in Britain and coal and nuclear use is decreasing rapidly.

An ancillary problem appears when one looks at energy demand and its increases in Britain recently. This is the fact that about 30% of this increased demand is involved in energy industry "losses." Solving this loss problem would also decrease energy "demand."

He states that although Britain is still a hydrocarbon exporter that this is going to change very quickly and then the UK will become more and more vulnerable to price fluctuations seen in other countries. He also states that Britain is going to have to start thinking in very large terms in order to replace dwindling supplies of hydrocarbon energy resources and that the white paper does not address this issue.

In direct contradiction to the primary driver for the white paper he sees the trend for emissions to rise after 2010 as nuclear power plants go off stream. He states that there is no way around this unless you spend a great deal of money on introducing renewable

energy sources. The white paper calls for meeting target emission levels in the future and, he says, just assumes that there will be a massive increase in renewable energy. He looks at the introduction of sequestration technology as an interesting and very exciting way to begin to tap into Britain's vast coal reserves again.

A positive side to the white paper is its desire to internalize environmental cost of the price of energy and thus to level the playing field and let the market decide which future energy technologies will emerge. Into this environmental internalization he injects the issue of nuclear energy and predicts that the government will have to reopen the debate on nuclear energy in the future.

Prof. Hassard was asked his opinion about the future of wind power, especially in the UK. He was personally optimistic about the future of wind energy in Britain and stated that he did not subscribe to the widely held belief that just because an energy source was renewable that it could not be implemented economically or to meet needed demand. He ended by stating that it appeared that it would be very difficult for Britain to meet the Kyoto obligations in the future and that the white paper did not appear to commit strongly enough to reaching those future goals. New technology is available but the commitment to institute that technology was not yet available.

Paul B. Weisz (Professor Emeritus, U. of PA) gave "an assessment of the choices of source energies offered by nature, their effective magnitudes that remain or will be available in the future in view of energy demand, population expansion and land area involvement". Historically, man's early energy source was solar derived. But in the last 200 years fossil energy, and, very lately, nuclear energy have initiated an exponential demand for energy. The U.S. consumption of energy in the year 200 was ca. 100 Quads (1 Quad = 1015 BTU) of which 85% is based on fossil fuels, of which 60 % of petroleum is dependent on imports.

Domestic U.S. petroleum resources would provide less than 25 years of current demand, the ANWR field (if opened) providing only 1.4 additional years. U.S. reserves of natural gas would provide 45 years at 1.1% population growth. U.S. coal reserves are large which at 1.1% population growth would last 130 years at current demand. But coal is the largest contributor to the CO_2 problem. Solar energy is limited in rate of arrival and in surface area that can be dedicated to its capture. The average U.S. arrival of solar energy is ca. 22 Quads/million acres. (To put it in perspective, 10 million acres is roughly the areas of Maine, Connecticut and half of Alabama). But photovoltaic cells are only 10-20% efficient, biomass (photosynthesis) is ca. 0.1 % efficient, with high grade energy conversion by ethanol being only 0.03 % efficient. Thus, land area requirements would be tremendous.

"Hydrogen is not a source energy. It can be produced only by consumption of a greater amount of an already existing source energy supply. It's benefit for CO_2-free combustion is negated by the CO_2 at hydrogen production from fossil fuels." In conclusion, current source energy supplies cannot sustain growing U.S. (and world) energy demand for more than a human life span (75 years). The gain in realistic energy conservation efforts would

be nullified within a decade by population growth. Serious educational efforts are needed to better public understanding of energy necessities, magnitudes and constraints by basic scientific laws. Our basic choices are: large scale PV cell technology, wind and solar heat (small contribution), biomass (highly inefficient), and nuclear. And to paraphrase Dr. Weisz “Nuclear source energy beyond uranium technology (I.e. fusion) is MANDATORY.”

Captain Stuart Funk (Deputy Director of Defense Energy Support Center, Fort Belvoir, VA) gave an overview of the current energy picture for DOD. DOD has established the Defense Energy Support as the military/war fighters single, centralized source for all energy needs. DESC manages all government owned fuel facilities and has 800 military and civilian employees worldwide to maintain all DOD energy needs on a continual basis. By far the single greatest part of DESC business is supplying $4.8 billion worth of jet and diesel fuel for mobility of the armed forces. The remaining $600 million of business is to supply coal, natural gas, electricity, bunker fuels and specialty items such as missile fuel.

The current world wide business is being operated by the Fuels Automated System, which is a web-based system geared to minimizing costs of energy to the government/DOD. DESC also monitors emerging trends in the energy business. These include fuel cells, hydrogen, liquefied natural gas, renewable energy sources and commercial development projects for Fischer Tropsch (gas to liquid) projects.

A recently funded study by DESC projected energy trends out to 2010. This study found that very few changes would take place in the near term either for fuels or engines. The major driver immediately beyond 2010 would be increasing environmental regulations that would eventually make noticeable changes in fuel quality and in engine developments. DESC functions currently as a customer focused organization with product and industry knowledge, which is geared to the immediate needs of DOD.

Mathew Simmons (CEO Simmons and Company) opened the discussion with a description of the recent energy meetings and conferences that he had participated in. He stated that he had analyzed energy problems for 35 years. He said that it is a very difficult problem even to provide an analysis of the history of energy, and more challenging to project the future of energy resources.

Simmons described the strong views of the many energy experts and the wide range of their views of the future of energy. He stated that one of the best energy forecast ever given was by Dr. M. King Hubbert in 1956 when he predicted when petroleum production would peak in the lower U.S. He said that many of Hubbert's critics laughed at him.

He described in detail the many bad forecasts that where made between 1980 and 2006 with the numerous price fluctuations. An in-depth presentation was made of the natural gas history, including storage fluctuations, drilling rates, and price fluctuations. He, also,

estimated the supplies in the United States and Canada. At the end he described the current price increase and the dire shortage we can have depending on the weather.

Simmons pointed out the closing of research facilities by the oil industry and the limited income and capacity of the refineries demonstrated that the oil companies could see that oil was running out and their investment would not be recovered. He also said that DOE was not supporting enough research and technology. A review of the world's oil fields and the reserves with the conclusion that OPEC still controlled the major reserves with Saudi Arabia having the most.

He refers to a number of energy scientists who predict that world oil will peak in the near future, with Saudi Arabia peaking now. He indicated that the experts stated that there were no more major reserve fields to be found and that the declining discoveries of small fields was continuing. Peaking in energy terms means that once we have received a peak, further growth in supplies is over. This does not mean that we are running out of oil, just reaching the maximum production. He admitted that he had never thought of peaking and neither had most people. It was thought that most wells would reach a maximum level and flatten out. He remarked that the method by Dr. Hubbert had proven to be the most important of all projections.

He elaborated on the increase in world population, recognizing its importance in the energy problem. His final statement was if the world ran short of oil and gas that "the future could be quite ugly."

CONCLUSIONS

Dennis Hardy, Bhakta Rath, Burton Hurdle, Homer Carhart, Fred Saalfeld, Robert Armstrong, Timothy Coffey, Jill Dahlburg

The Department of Energy projects total world consumption to increase by 59% between 1999 and 2020, from 382 to 607 quadrillion ($x10^{15}$) BTUs per year. The same report predicts a 20% increase of carbon dioxide emissions equivalent to approximately 10 billion metric pounds of carbon. As the nations strive to improve standards of living energy usage will increase significantly resulting in increasing competition for the world's energy resources.

The impact of these projections on the Department of Defense will be profound since hydrocarbon based products derived from fossil fuels have been the primary energy source and critical to U.S. military strength and missions throughout the 20th century. Indeed, the question of energy supply and cost for the 21st century will become more critical to DOD in the future.

To come to grips with this situation several questions were posed at the beginning of the Energy Workshop Series:

- What should the Department of Defense do in the near term to engage with the oil and gas industries as they continue to evaluate future energy sources for production?
- What role should DOD take on national and international future energy programs?
- What should be the long-term Department of Defense strategies and policies in regard to future potential energy shortages?
- What are the estimates for future availability of hydrocarbon fuels in light of projected global and national demand?
- What are the economics of supply and demand for alternate fuels and what effect will this have on DOD?
- What are the environmental constraints and the legal implications of a hydrocarbon fuel shortage to the Department of Defense?

In response to these questions workshop participants made an effort to understand the role of economics and geopolitics as well as the technological issues related to the use of alternate fuel sources within the DOD.

It was generally agreed that, for the next 50 years DOD will require liquid hydrocarbon fuels and that environmental considerations are now a must in the quest for energy security. There was not general agreement about whether this continued requirement could be met. This lack of agreement about supply should be treated as an important indication that DOD should continue to monitor closely and take appropriate actions as necessary the question of future energy resources.

To achieve this energy security requires a national energy policy, which is balanced and includes conservation and energy efficiency guidelines and goals. The policy must also contain guidance on renewable energy and have a plan to increase renewable energy much more quickly than business as usual. It must take a sensible position on climate change. It should reflect steady economic growth and national security.

The risk of non action on this matter was generally agreed to be quite significant and that DOD should initiate and maintain an independent comprehensive study of alternative fuel sources and support the development where possible and appropriate for critical future needs. It should be noted that a focal point for action within DOD and also the three Services on future energy matters at the Secretariat level is not now established. In the following we will highlight some of the material, which was presented to support these conclusions and some of the views, which challenged these conclusions.

For the last 25 years the growth and transportation demand for oil grew twice as fast in Asia than in the rest of the world. Asian-Pacific countries consume more oil than the United States and import most of their oil from the Persian Gulf. This has very strong political implications.

To fully supply the expected liquid natural gas needs of the U.S. will require 400 to 500 large cargos of liquid natural gas tankers transiting U.S. waterways or harbors in a given year. This raises serious issues and problems, among them security and safety of supplies.

It was noted that no large (greater than 1 billion barrels) oil fields have been discovered in the United States since 1960. Current U.S. average oil consumption including imports is between 5 and 6 billion barrels per year.

The economists took the position that the impending oil crisis is exaggerated and argued that the so called ultimately recoverable resources (URR) metric is not a measure of total world resources but rather an estimate of the total recoverable portion of that resource at the current technology level and prices. They agreed with current estimates of URR of about two trillion barrels but argued that if one removes the economic and technological constraints the amount of oil resource becomes about eight trillion barrels. They further argued that world discoveries have not dropped but have been about 10 billion barrels per year for the last 10 years of the 20th century. (Compare this, however, to current world total consumption of about 27 billion barrels per year). They believe that the primary drivers should not be scarcity but the ability to provide cheaper energy than currently available.

It was suggested that one possible reason for the lack of reinvestment in the future growth of the oil industry is that the amount of reserves per well (or per 1,000 ft. of hole drilled) has been coming down markedly thereby discouraging reinvestment and that with the world currently consuming 27 billion bar. of oil per year even exploitation of the Caspian Sea regions would only supply the world for six months.

A general conclusion was that the current global situation of oil producing countries was tenuous and required watching because of the political and economic linkages of energy stores.

There was a sense that energy is the biggest challenge faced by humanity today and that current technology will not be able to provide the required energy. A number of alternative technologies were discussed including bio mass, renewable ocean sources (wave, tidal, and thermal), gas hydrates, and hydrogen.

During the *biomass* portion of the symposium there was intense debate regarding the net energy value for ethanol production. While the disagreement on this matter was not resolved it served to illustrate the current wide range of conclusions among serious researchers in this field. Energy crops have been an active area of research for several years. Farmers could use their marginal land for such crops. Fast-growing trees and shrubs and grasses are good candidates for energy crops.

The readily available feedstock of raw materials is not the problem in ethanol production. The development of more efficient technology, especially improved enzymes for the conversion of lignocelluloses, appears to be key to making these materials economically feasible.

There are different opinions regarding the environmental effects of ethanol. The issue of ethanol production is not just a topic of scientific and technical debate and policy decisions made about ethanol may likely have a large political component. Also, most of current ethanol production really is not from biomass but from grain. Until the economics of the enzymatic treatment of lignocelluloses improves this is likely to continue to be the case.

It was noted that the *ocean* is the largest solar collector in the world and receives in one day about 8 times the energy equivalent of the world's annual oil consumption. One tenth of one percent of the energy in ocean waves is the equivalent of five times the world's energy requirements. The main disadvantage of tidal power is that it is limited to about 40 sites worldwide and that is very costly to construct such systems. The best wave energy sources are above the Tropic of Cancer and below the Tropic of Capricorn. The total wave energy in these regions is equivalent to about twice the world's current electricity production.

Another potential source of energy from the oceans involves exploiting the ocean thermal gradient. It was noted that the low temperature cycles involved would likely require specially designed plants using principles unlike typical power plant principles. It was

stated that such plants would produce power at prices competitive with hydroelectric plants.

Regarding gas *hydrates*, it was noted that many gas hydrates are stable in deep ocean conditions and that methane hydrates are by far the dominant making up > 99% of gas hydrate naturally occurring on the ocean floor. The organic carbon in gas hydrate is estimated to be twice as much as in all fossil fuels on earth including coal. The presence of gas hydrates has been reported all around the world but most commonly around the edges of the continents. The future of gas hydrates as an energy resource depends on the evolution of geological studies, engineering studies, economics, and politics.

It is anticipated that the necessary knowledge base for commercial production with minimal impact on the environment and the technology suitable for economically extracting methane will be available by the year 2015. Industry's view is that, at the current state of the art of infrastructure and drilling technologies, investing in a stand-alone hydrate extraction scheme is uneconomic at current U.S. natural gas prices. It is clear that the U.S. will have to import a large part of its natural gas energy early in the 21st century and that substantial R&D needs to be done if methane hydrates are to provide relief. There will also be associated policies with respect to deep water drilling that will need to be addressed.

To address the multiple concerns associated with fossil fuel depletion and greenhouse gas production, *hydrogen* has been proposed as a potential energy storage medium. In order to transition to a hydrogen economy a number of critical part technologies must be pursued. These are associated with increasing performance efficiency and/or reducing costs in the areas of compact light weight hydrogen storage for transportation purposes; hydrogen production; fuel cells; and carbon sequestration.

It was noted that coal was especially attractive as a hydrogen feedstock for the reasons that is abundant globally and extensive coal mining and processing infrastructure is already in place. A major issue with respect to coal gasification for the production of hydrogen is the disposal of residual carbon dioxide. There are several approaches this issue. These include deep ocean disposal; disposal in geological media such as depleted oil and gas fields; and disposal as carbonate rocks. It is important determine as soon as possible if geological storage of carbon dioxide is viable.

The challenges to transition of fuel cells involves issues such as hydrogen cost, performance, reliability, safety, consumer acceptance, and the development of the approaches for the necessary infrastructure. Also codes and standards for fuelling, distribution, and consumer products must be provided.

It became clear that regional dynamics, distribution distance and capital utilization would shape hydrogen infrastructure development. Overall, considerable hurdles remain before significant progress can be made toward a commercially viable hydrogen economy. DOD must remain cognizant of the progress. All the critical path technologies such as

hydrogen production, storage, fuel cells, and carbon sequestration may have military aspects.

In summary, the workshop series of did not provide definitive answers to the questions posed at the beginning of the series and restated at the beginning of this chapter. The series did, however, provide a reasonable definition of the issues and of the areas, which require detailed study. As to the question "energy crisis, fact or fiction?", the answer is both, depending on the time horizon. It seems clear that there is no imminent crisis regarding energy supply or cost for DOD. It also seems clear that a major crisis is building, although there is considerable disagreement regarding when it will occur. In some sense this disagreement is irrelevant, because the time involved in providing the alternative solutions needed to cope with a crisis likely exceeds the uncertainty regarding when it will occur. The associated costs just for DOD will be huge. It is recommended, therefore, that DOD build upon this workshop series and proceed to conduct an in-depth study of the science and technology required to meet future energy needs. The results of this study will supply the Secretariat with the requisite background to formulate DOD energy policy for the 21st century.

RECOMMENDATIONS

Recommendation 1:

A position responsible for future DOD energy policy and problems should be established immediately in the office of the Undersecretary of Defense for Policy. This person should report directly to the Secretary of Defense and coordinate with similar corresponding positions established in each of the services. This person will also coordinate with other offices in DOD associated with fuels and energy and with DOE.

Recommendation 2:

It is recommended that DOD immediately start an in-depth study of science and technology required for its future fuel and energy needs and problems. This study should do the following:

- Develop timelines and plans for ways of replacing/supplementing liquid petroleum fuels.
- Evaluate DOD fuels and energy needs for: aircraft, tanks, ships, submarines, rockets, missiles, bases, and remote bases.
- Formulate and fund individual panels with service representatives to address issues such as: chemical fuels and energies, nuclear energy, electromagnetic energy, thermal energy, mechanical energy, hybrid energy technologies, and exotic energy sources. A steering committee will coordinate the work of these panels.
- Organize panels by drawing on appropriate experts from the government (especially DOE), academia and industry. Each panel will consider the following topics: increased utilization of fossil fuels other than petroleum (particularly gas hydrates); all possible and potential sources of energy; safety issues; system and fuel efficiency; environmental factors; economics and impact on operations, quality, and logistics. This study should be completed in one year.
- Provide a prioritized execution plan for the short-, mid-, and long-term with emphasis on S&T and R&D requirements specifically for DOD.
- The steering committee will present the results of this study directly to the Undersecretary of Defense and to DOE.

ACKNOWLEDGEMENTS

The Organizers and editors of the workshops (F. E. Saalfeld, T. Coffey, B. B. Rath, D. R. Hardy, B. G. Hurdle, H. W. Carhart, and M. Baranick) wish to acknowledge the financial support of the Office of Naval Research, the Naval Research Laboratory, the National Energy Technology Laboratory of the Department of Energy and the ONR-International Field Office. The assistance of Kathleen Jabs, and Gina Cordero is gratefully acknowledged, as is the invaluable contribution of Steven Gill in organizing the workshop and compiling and editing the manuscript.

FIGURES

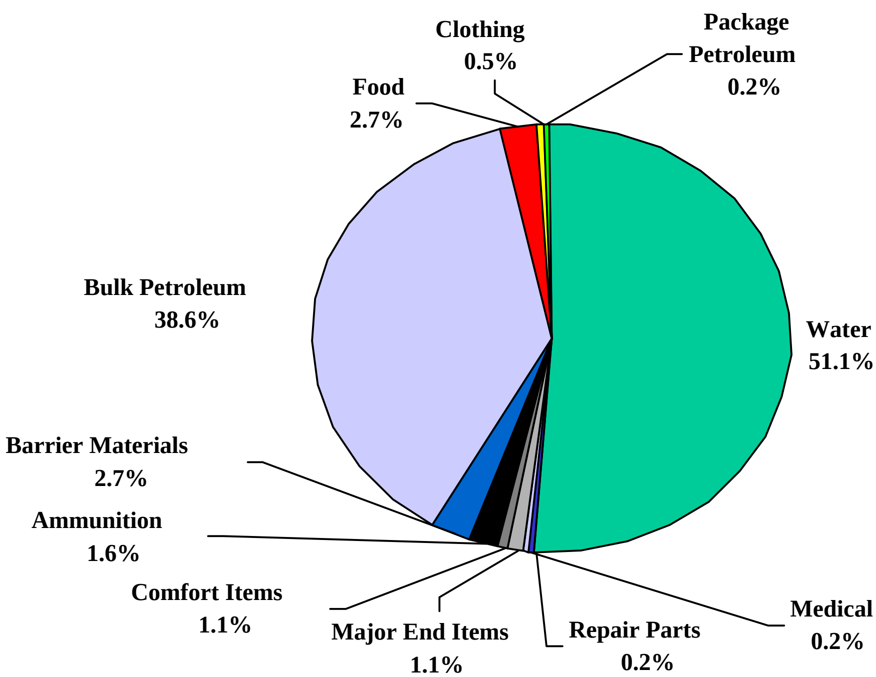

Figure 1. US Army Battlefield Logistical Demands
(Adapted from Valdes[i])

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[i] James J. Valdes, "Biotechnology Executive Roundtable," presentation to GEN Paul J. Kern, Commander, US Army Materiel Command, undated.

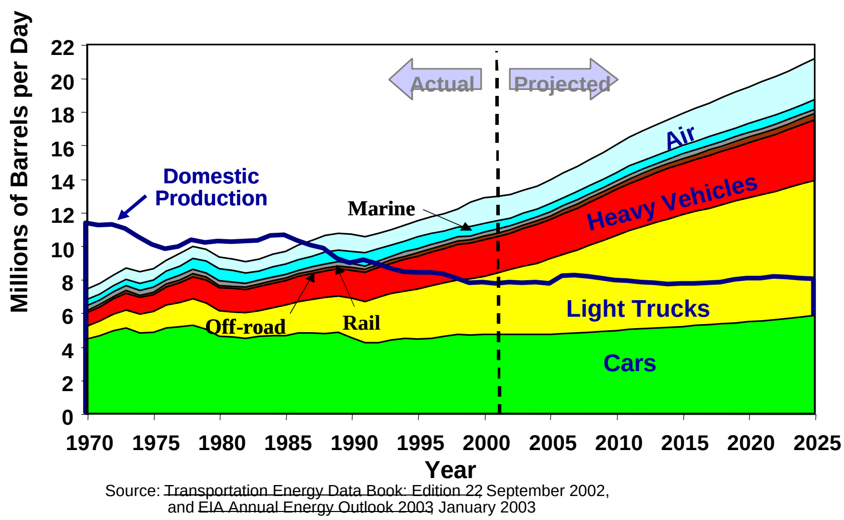


Figure 2. Actual and Projected U.S. Petroleum Consumption by Vehicle Type

For transportation only. U.S. consumption exceeded domestic production in the mid 1980's and will continue to rise to nearly 70% by 2025.

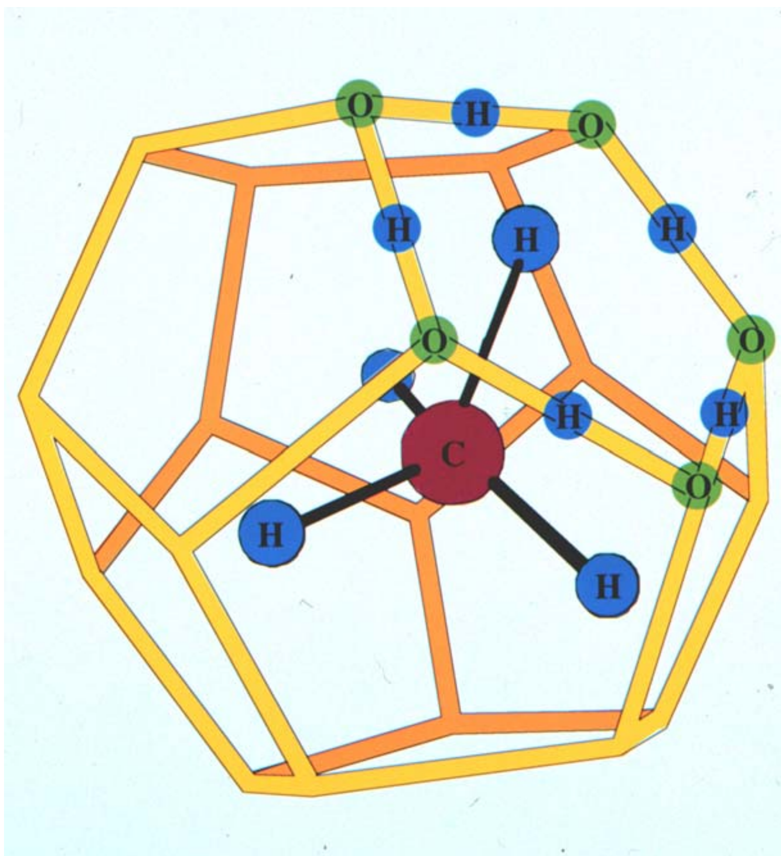


Figure 3. Diagrammatic Concept of a Structure I Gas Hydrate Cage Holding a Methane Molecule

H, O, and C represent hydrogen, oxygen and carbon atoms. Double lines, filled or unfilled, represent chemical bonds.

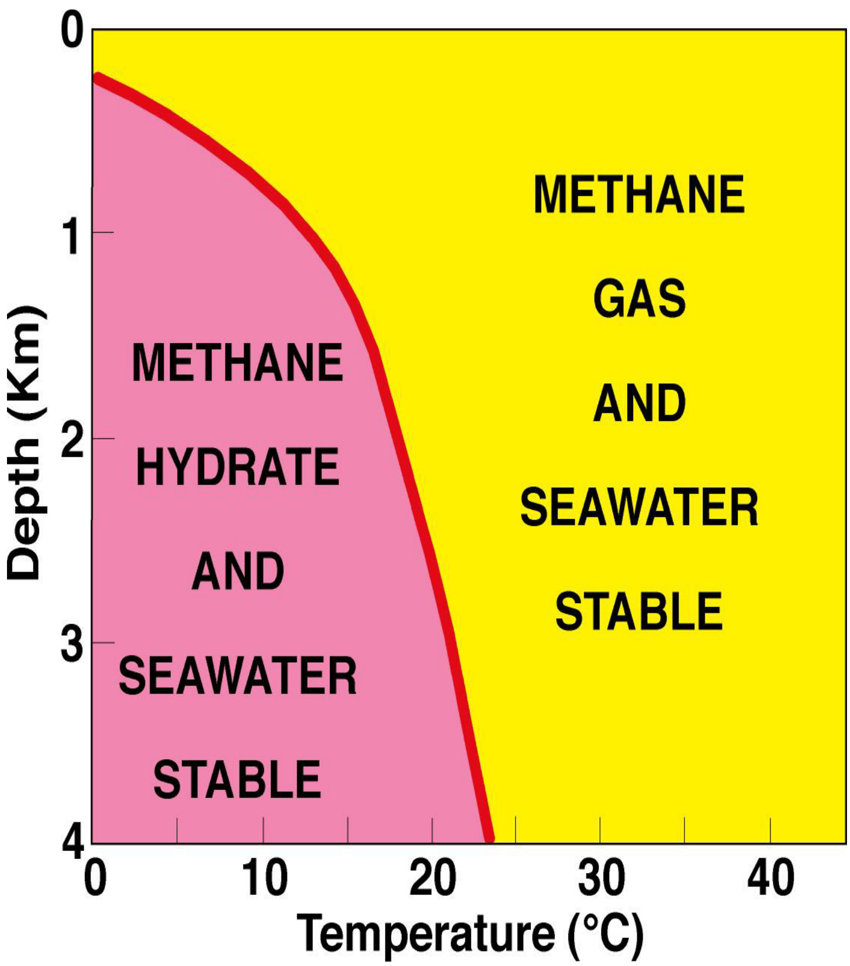


Figure 4. Phase Boundary of Methane Hydrate in the Ocean (solid line)

The pressure axis has been converted to depth into the ocean, so pressure increases downward.

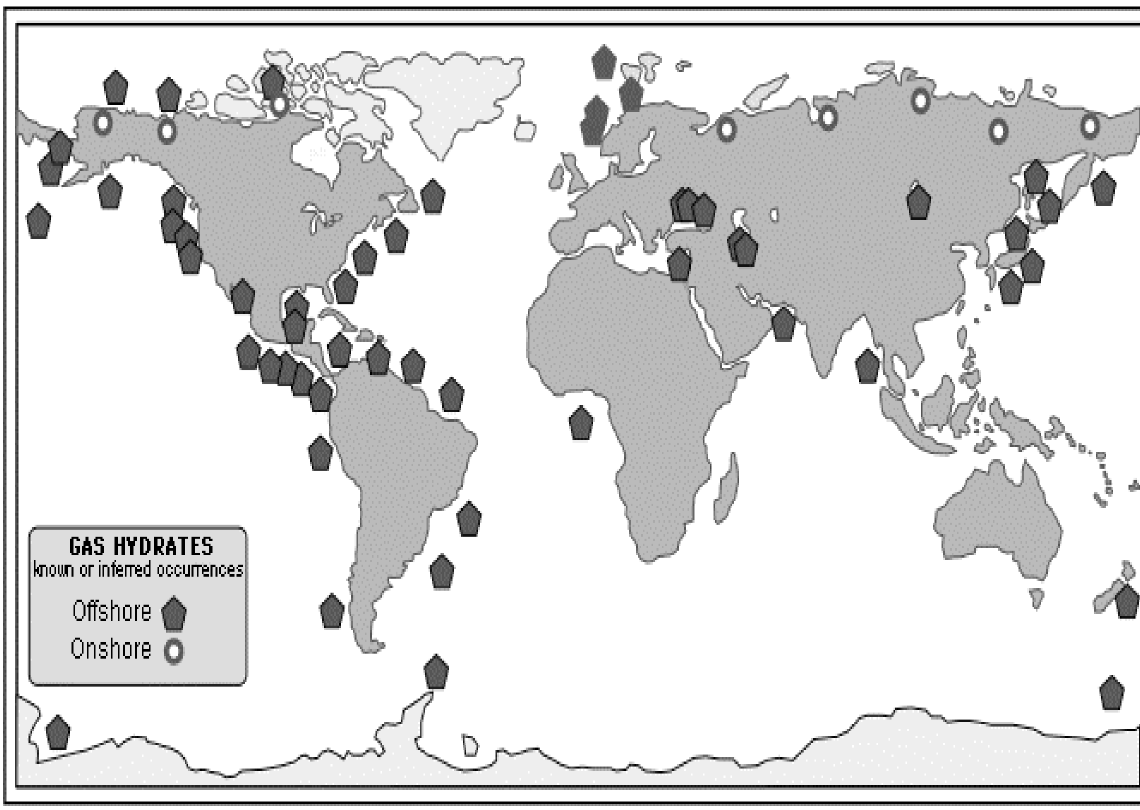


Figure 5. Global Distribution of Confirmed or Inferred Gas Hydrate Sites, 1997 (courtesy of James Booth, U.S. Geological Survey). This information represents our very limited knowledge. Gas hydrate probably is present in essentially all continental margins.

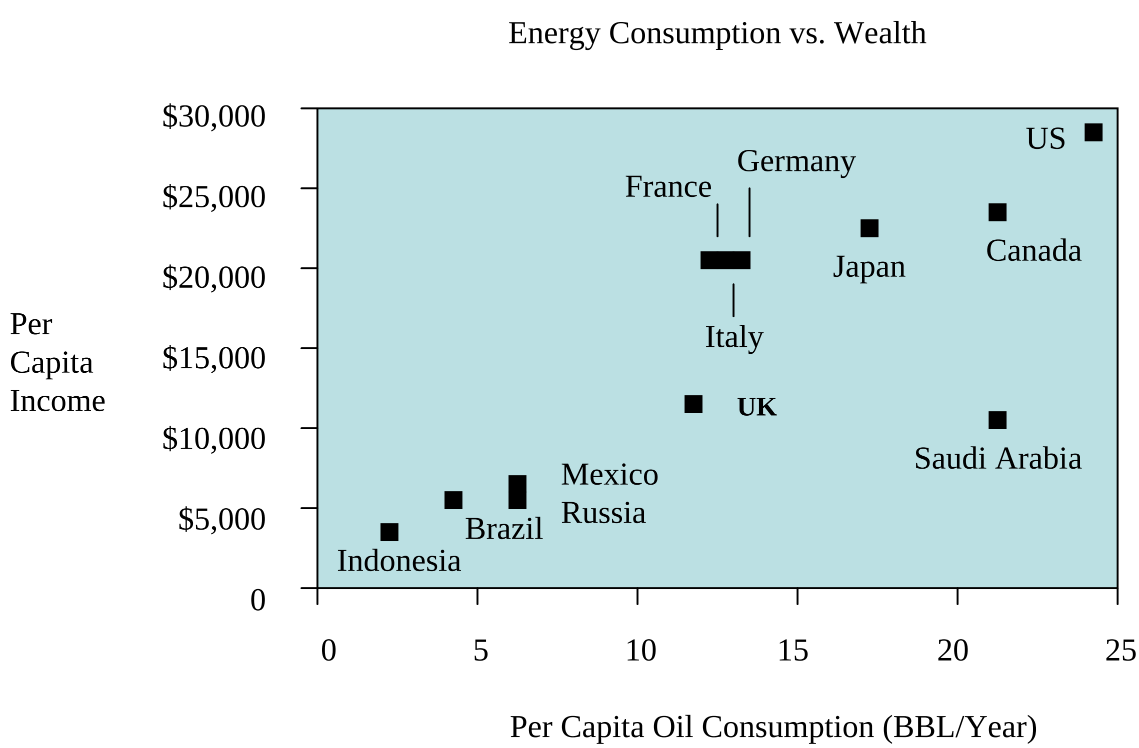


Figure 6. Global View of Future Energy Resource and Demand

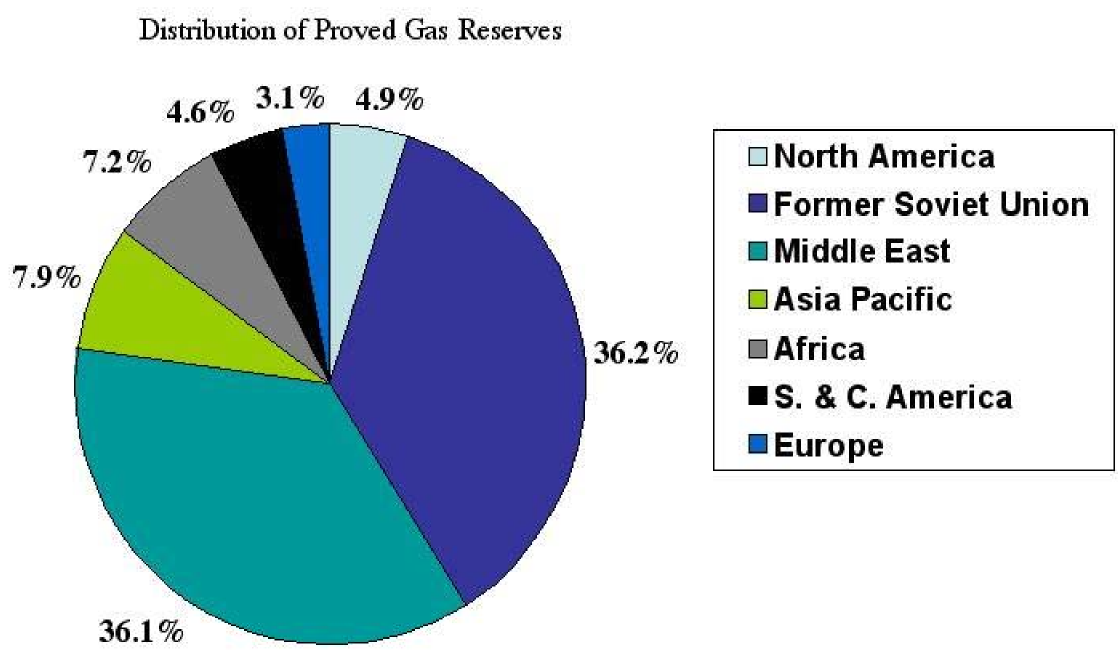


Figure 7. Global Distribution of Gas Reserves

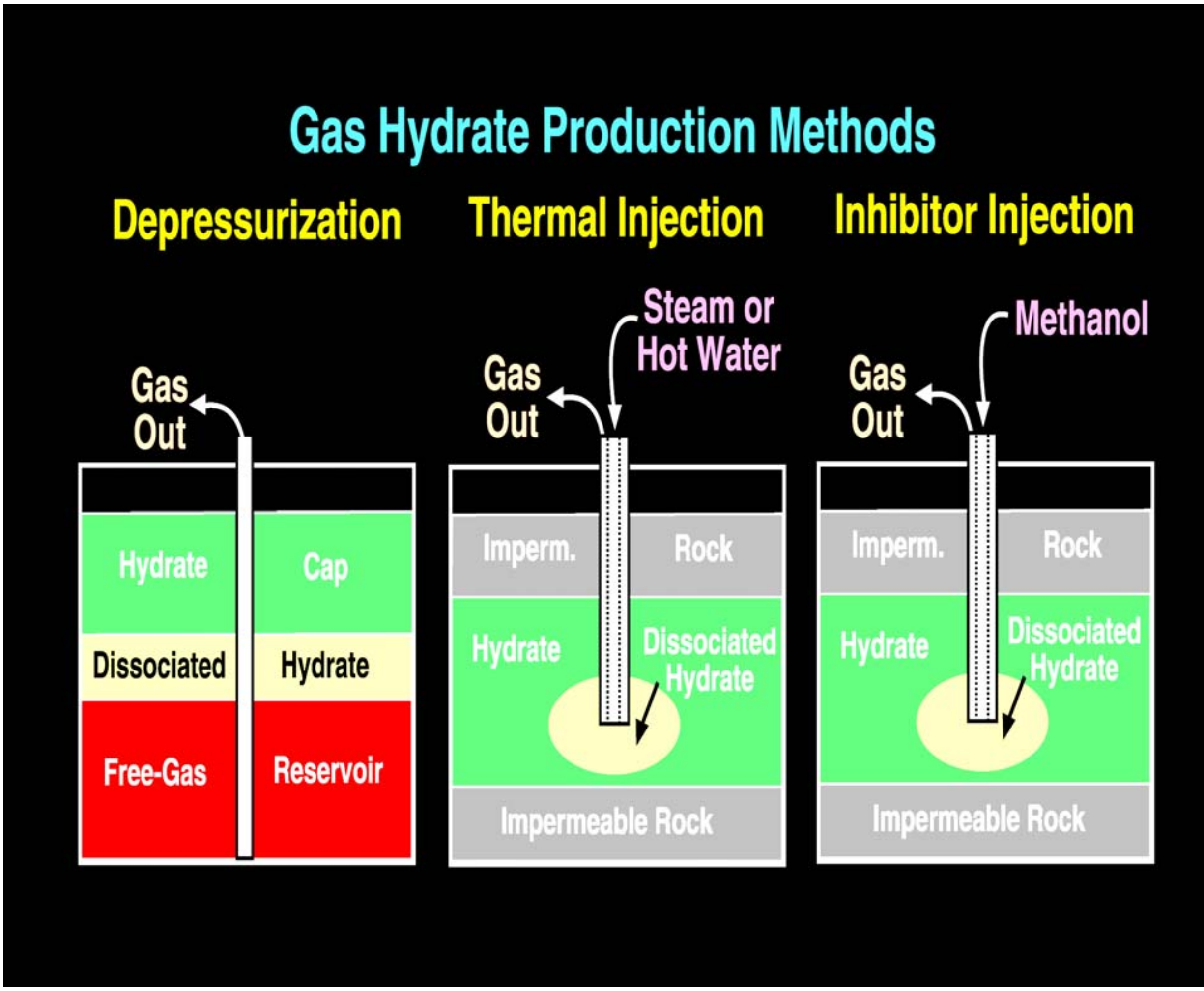
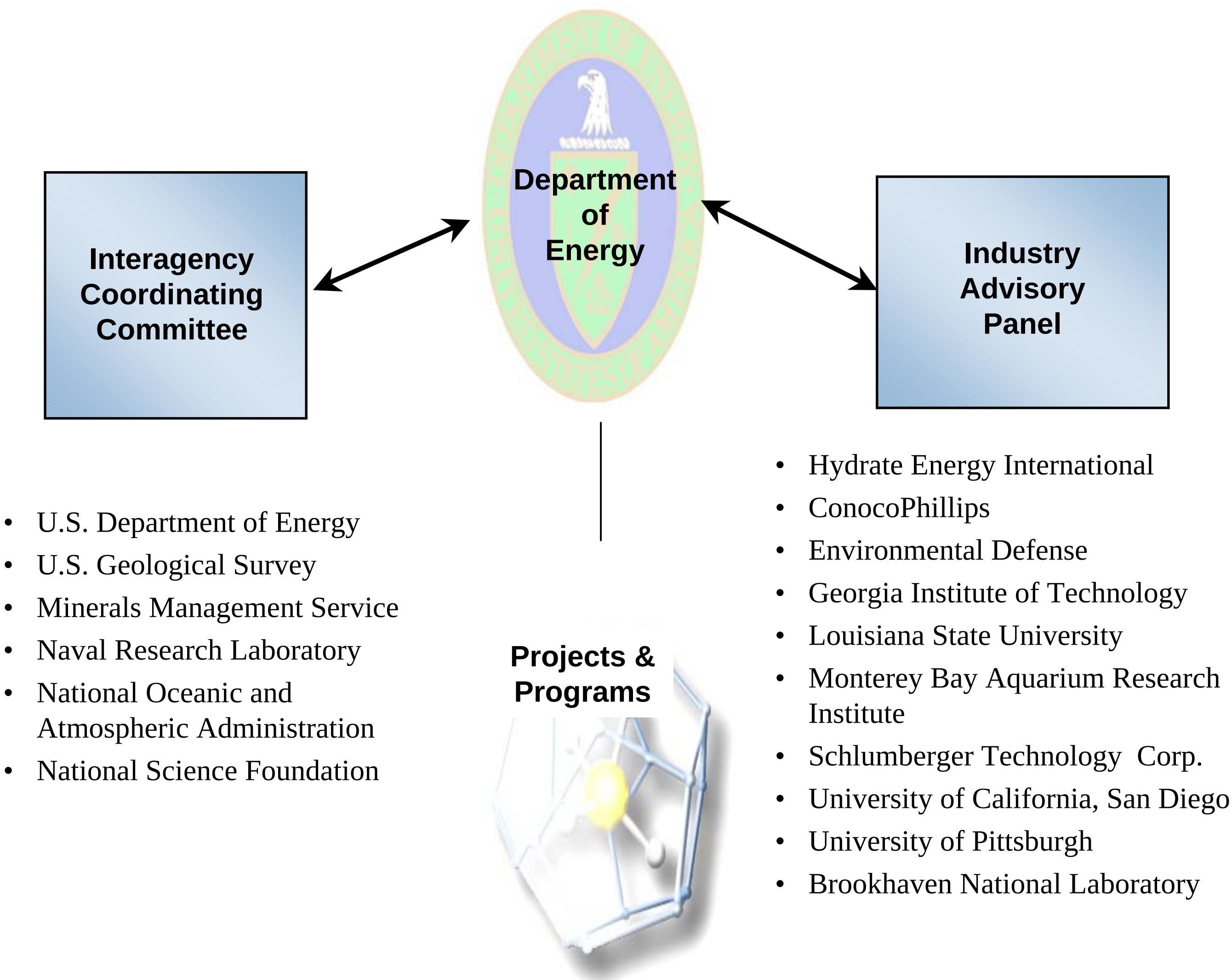


Figure 8. Approaches to Gas Extraction



Based on Methane Hydrates Act of 2000

Figure 9. National Methane Hydrates R&D Program

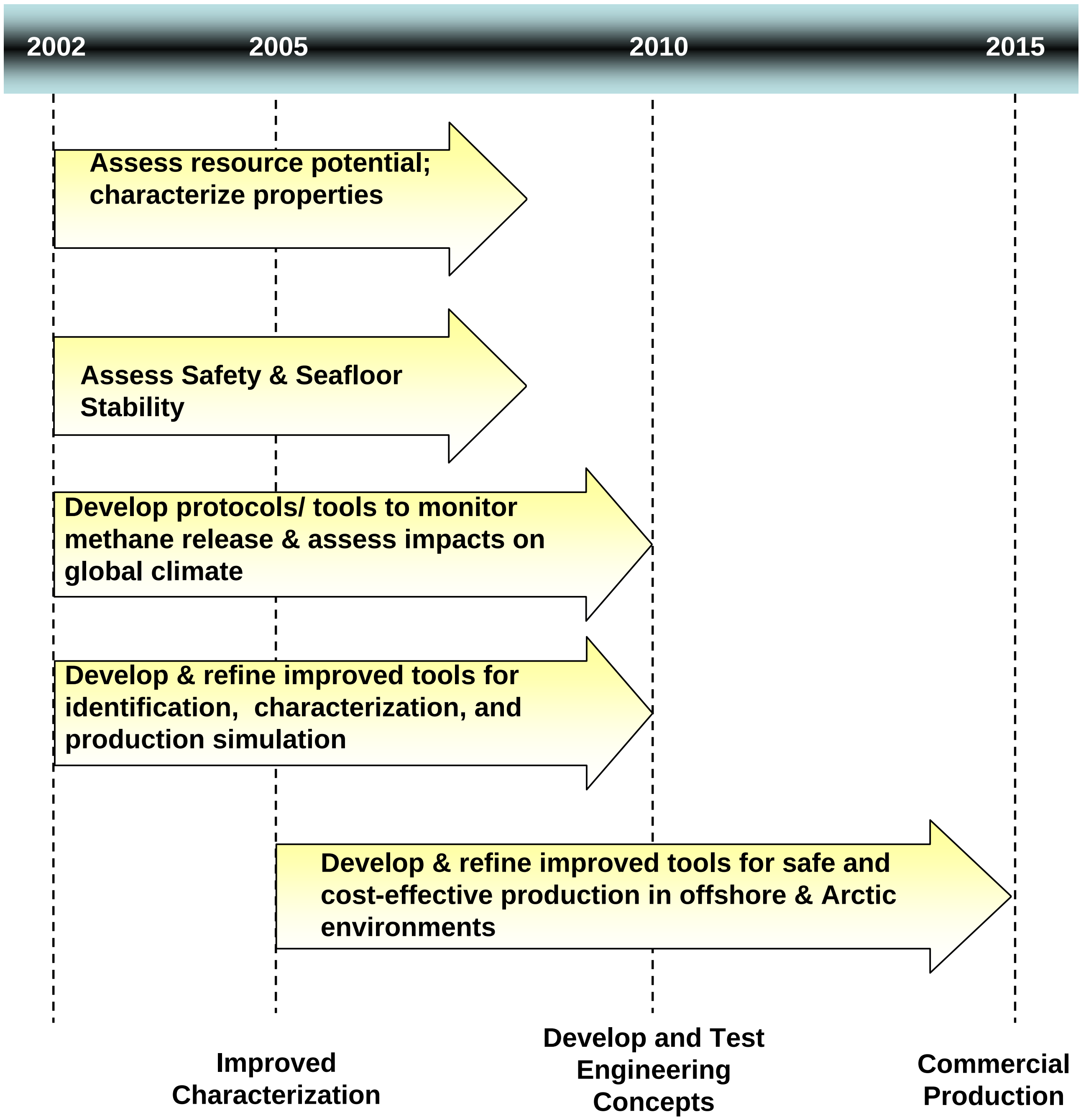


Figure 10. Methane Hydrate Technology Road Map

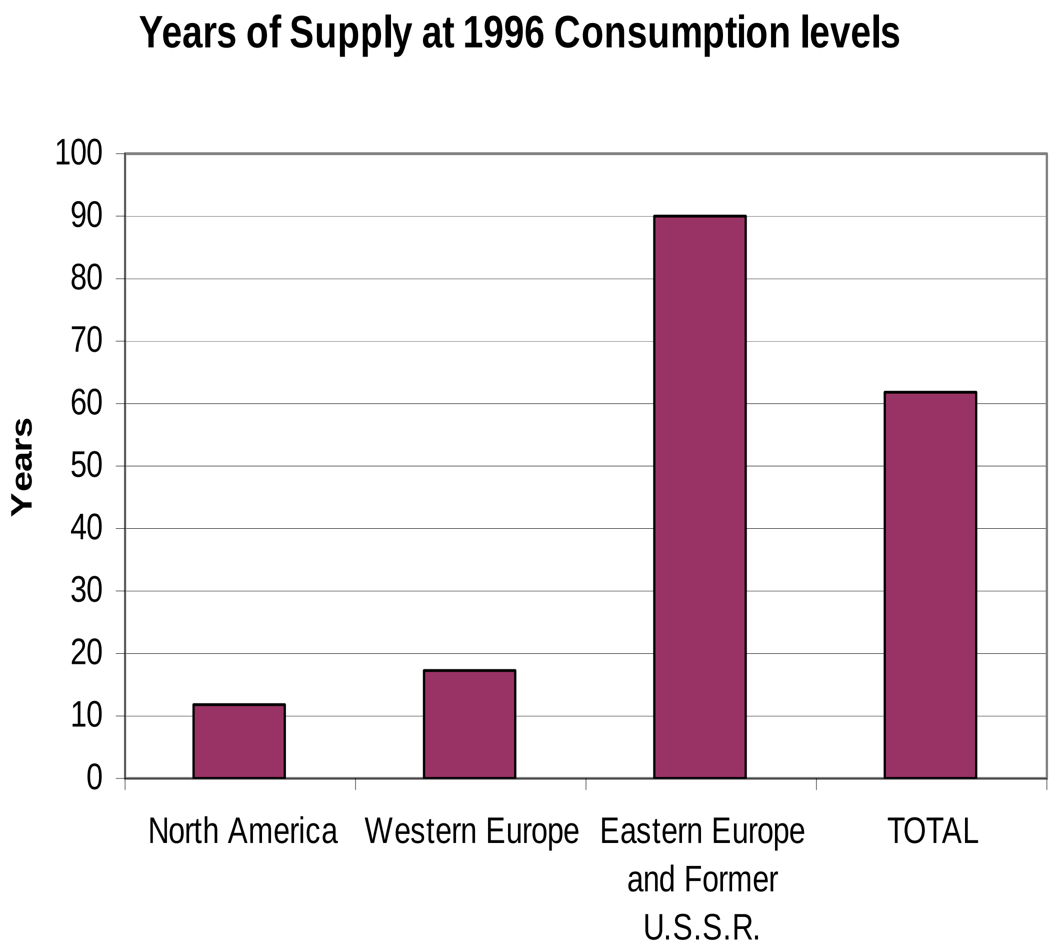


Figure 11. Years of Natural Gas Supply at 1996 Consumption Levels

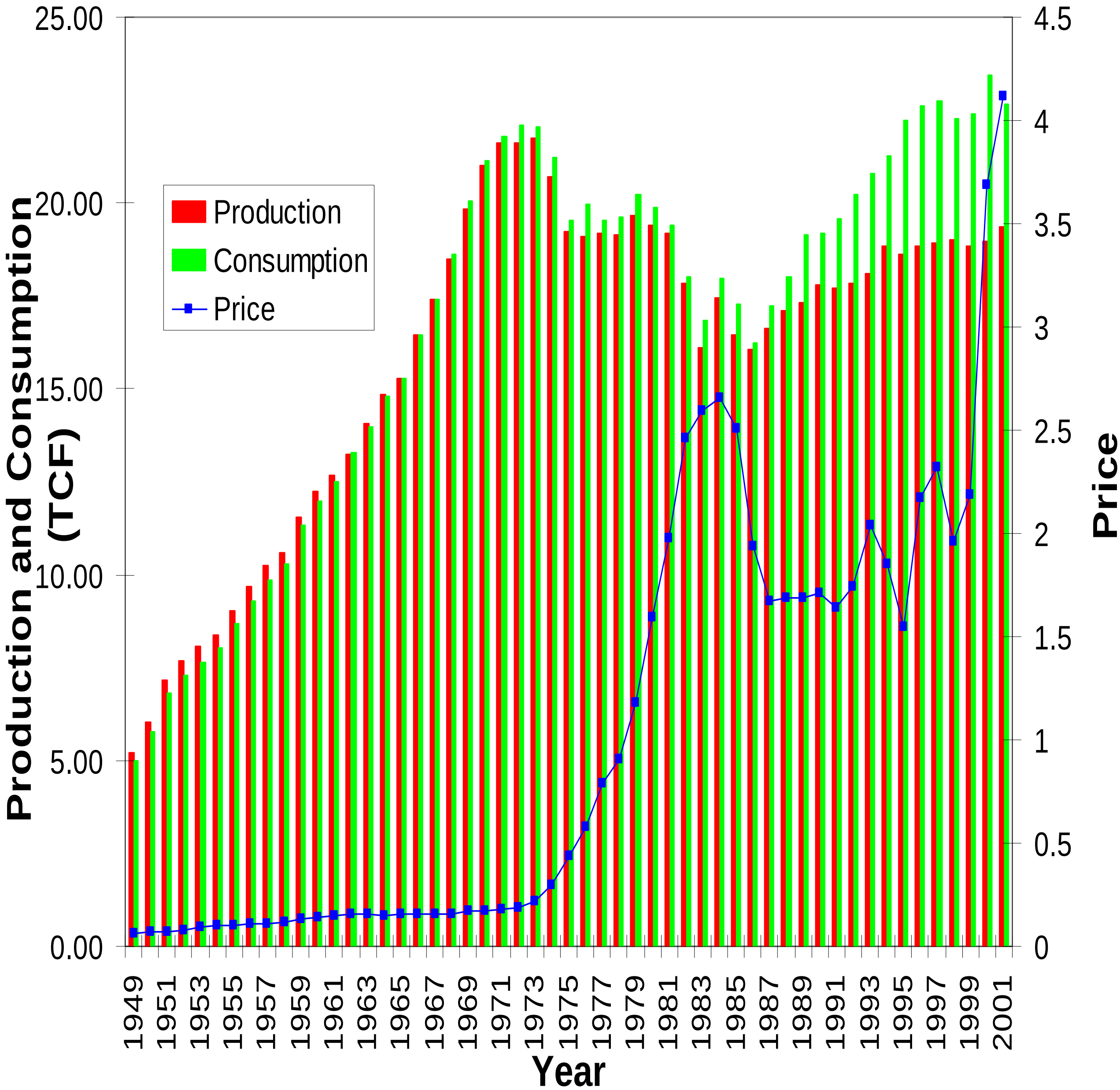


Figure 12. U.S. Natural Gas Price and Consumption.

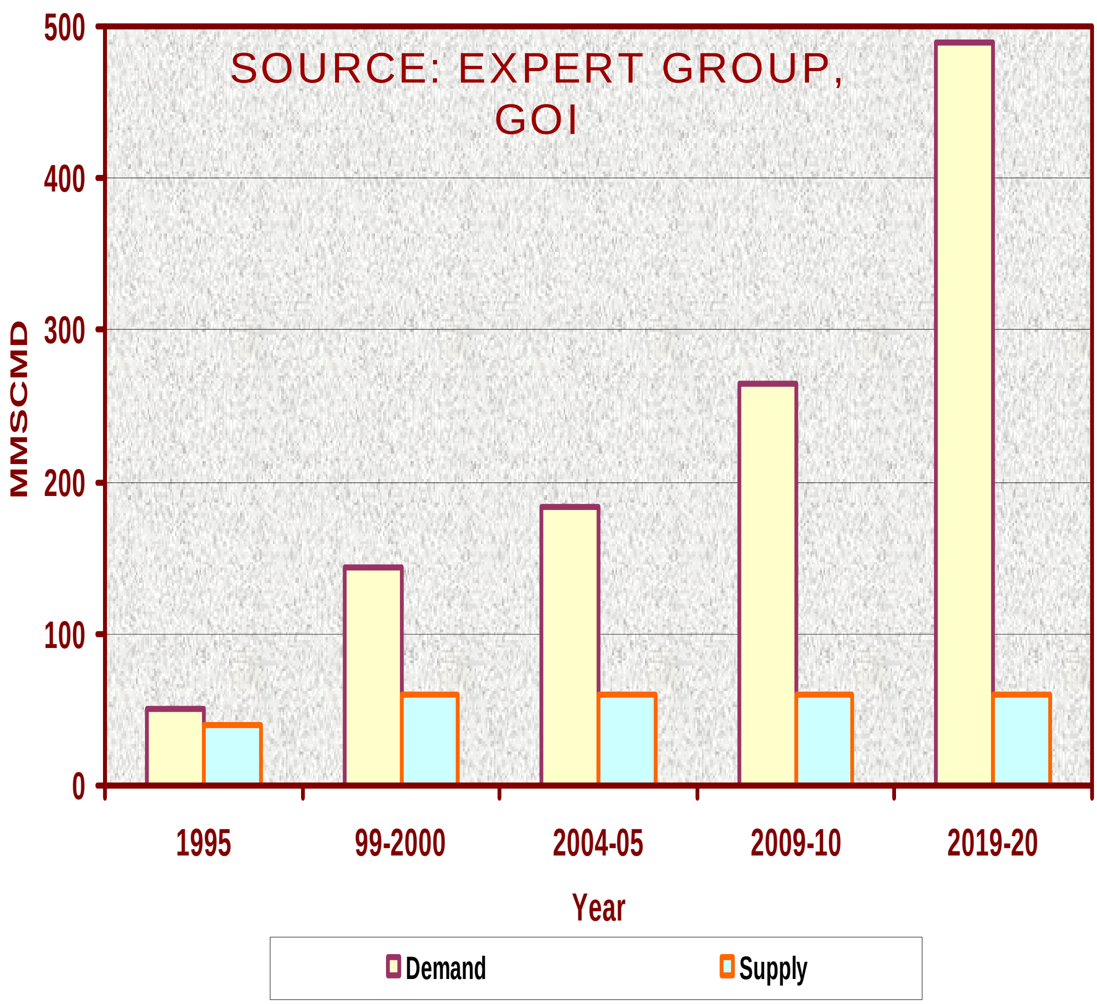


Figure 13. Natural Gas Demand and Supply in India

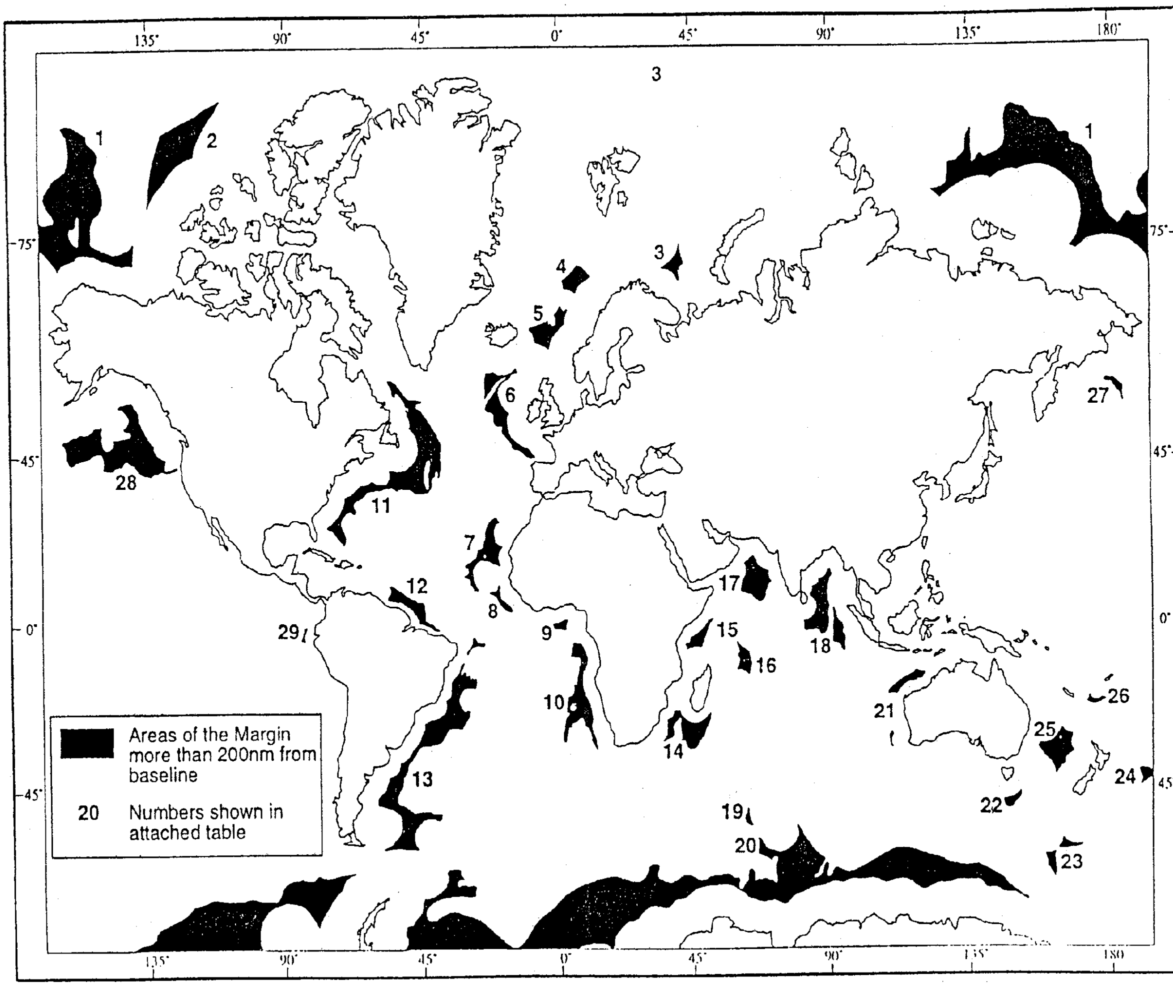


Figure14. Global View of the Continental Margins beyond 200 Nautical Miles from Baseline

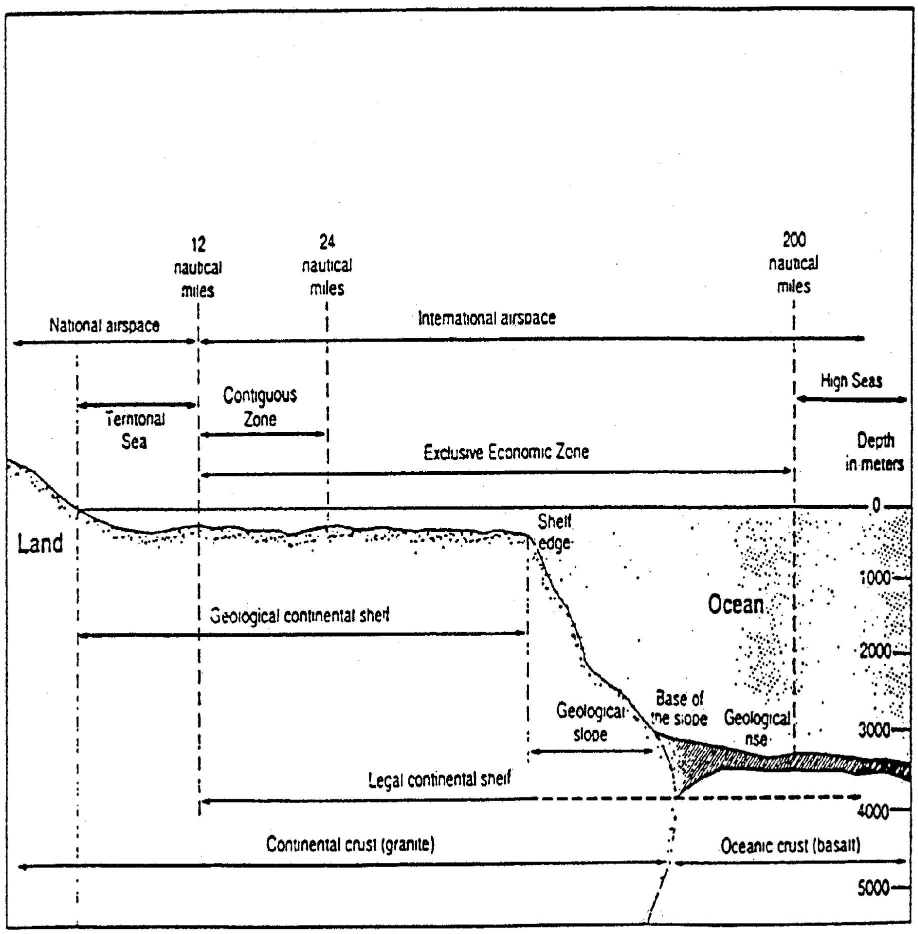


Figure The Legal Regimes and Geomorphic Regions

Figure 15. Legal Regimes and Geomorphic Regions